CIRCUIT AND RADIATION EFFECTS ANALYSIS BY ITERATED PROPAGATION OF BIVARIABLE RESPONSE FUNCTIONS

Robert G. Stewart, et al

Stewart Research Enterprises

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Air Force Weapons Laboratory

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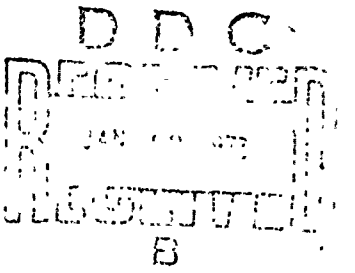

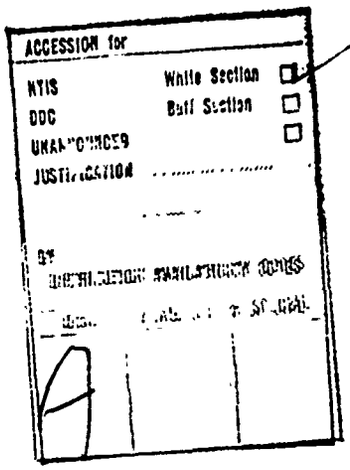

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13. ABSTRACT

(Distribution Limitation Statement A)

Radiation effects analysis of complex electronic circuits by computers presently is limited by core storage and long execution times. A new method, entitled Iterated Propagation of Bivariable Response Functions, treats components in the block sense using experimentally obtained time domain response or transfer functions. These functions are described in a three dimensional space of the input stimuli, output response, and time, by means of fitting the experimental data with cubic polynomials matched in the spline sense at interstices of the fitting grid. The basic data was obtained using conventional oscilloscopic techniques at the Kirtland AFB, flash X-ray facility and the Sandia pulse reactor. A computer program called SAP, adapted to work with SCEPTRE, uses a modified convolution process to calculate the electrical and the gamma and neutron radiation responses from the surface descriptions. These responses are then superimposed to obtain the combined response. Such a process is not rigorous but rather an engineering class of approximation. The results achieved ranged from fair to excellent, as applied to a 741 operational amplifier and a 9704 dual NAND gate. The three dimensional surfaces provide a vivid grasp of device performance and radiation response over the entire range of the stimulus variables.

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FOREWORD

This report was prepared by Stewart Research Enterprises, Los Altos, California, under Contract F29601-71-C-0039. The research was performed under Program Element 61102H, Project 5710, Subtask TB027, and was funded by the Defense Nuclear Agency (DNA) under MIPR 555-70.

Inclusive dates of research were February 1971 through April 1972. The report was submitted 1 September 1972 by the Air Force Weapons Laboratory Project Officer, Captain John M. Ives (ELT).

Dr. Robert G. Stewart was principal investigator. Dr. Peter S. Castro participated in all aspects of the work. The original technical motivation for this effort evolved from discussions with Dr. Julian Nichols and Captain John Anderson of AFWL. The radiation exposure jigs used at the Kirtland flash X ray and the Sandia pulse reactor were designed and built by Mr. Robert Youden. Mr. Robert Marshall of Fairchild Semiconductor and Captain Patrick Vail of AFWL helped in planning the device radiation exposures. The tests were conducted by Dr. Stewart and Mr. Youden with the assistance of Captain John Ives, AFWL project officer. Mr. Siu Kee Lee participated with Dr. Stewart and Dr. Castro in the tedious work of making the first three-dimensional plots. Mr. David Schrodi worked diligently in programming and debugging the computer codes. Mr. David A. Johnson lent valuable assistance with some of the more difficult programming problems. The principal investigator expresses here his appreciation to all of the above named individuals, and also to those at the Air Force Weapons Laboratory whose support made this research possible.

This technical report has been reviewed and is approved.

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ABSTRACT

(Distribution Limitation Statement A)

Radiation effects analysis of complex electronic circuits by computers presently is limited by core storage and long execution times. A new method, entitled Iterated Propagation of Bivariable Response Functions, treats components in the block sense using experimentally obtained time domain response or transfer functions . These functions are described in a three dimensional space of the input stimuli, output response, and time, by means of fitting the experimental data with cubic polynomials matched in the spline sense at interstices of the fitting grid. The basic data was obtained using conventional oscilloscopic techniques at the Kirtland AFB flash X-ray facility and the Sandia pulse reactor. A computer program called SAP, adapted to work with SCEPTRE, uses a modified convolution process to calculate the electrical and the gamma and neutron radiation responses from the surface descriptions. These responses are then superimposed to obtain the combined response. Such a process is not rigorous but rather an engineering class of approximation. The results achieved ranged from fair to excellent, as applied to a 741 operational amplifier and a 9704 dual NAND gate. The three dimensional surfaces provide a vivid grasp of device performance and radiation response over the entire range of the stimulus variables.

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continued

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SECTION I

INTRODUCTION

This report describes the ideas behind a block oriented computer analysis technique termed Bivariable Response Function Propagation and how these ideas were applied to the electrical and radiation responses of a linear integrated circuit operational amplifier and a digital NAND gate. The dynamical response of the circuits is represented using three-dimensional surfaces which were fit to experimental data acquired from neutron, gamma ray, and electrical pulse stimuli. The block response in a subsequent circuit or system analysis problem is calculated using these surfaces by a process which may be termed convolution in the nonlinear sense; hence, the process constitutes an approximate rather than a rigorous method. Nevertheless, computed results show reasonable agreement with those obtained experimentally. Further, the response function surfaces provide a rich and different insight into the effects of radiation on devices.

1. PRESENT PROBLEMS

The presently existing transient radiation effect codes have been extremely effective in enabling device and circuit designers to assess the validity of their designs prior to actually fabricating or building them. By developing physical understanding of the electrical characteristics of the device, and then learning how radiation alters these physical properties, one can:

- extrapolate test data to other dosages,
- determine best device geometry and circuit layout,
- alter physical parameters to improve device characteristics,
- ascertain radiation testing required and what measurements are needed.

Thus the existing programs such as SCEPTRE, TRAC, and NET have indeed been useful in meeting the primary goals for which they were devised.

Several aspects of the present computer modeling approaches are unacceptable, namely:

- core limitation on nodes,
- excessive execution time, say due to very small time constants,

- convergence problems with certain eigenvalues. This depends on whether implicit or explicit integration is used in the program.
- Package effects are not included in the equivalent circuit. These and EMP effects can cause major differences between predicted and observed radiation responses.
- expenses at the Nevada test site are very high. This type of testing is presently needed since there are no suitable computer programs for predicting performance of high complexity circuits. Note also that such test procedures only yield one point in the parameter space of the radiation stimulus and its effect.

2. EXISTING TECHNIQUES FOR MODELING

The primary method employed to determine circuit behavior today is to set up Kirchoff's laws for the nodes and meshes using topological trees, build the equivalent device models into a set of simultaneous algebraic and differential equations, and solve these by standard matrix inversion techniques. Generally sparse matrix procedures can be used to minimize core storage requirements. Implicit integration can be used to reduce solution time, and enhance convergence likelihood.

For more complex systems, state variable formulations, physical differential equations, Linvill's pseudo-linearization models, and analog-hybrid simulations are the primary procedures available. It is important to note these methods may require heavy experience on the part of the user with the modeling process. The accuracy of an analog or hybrid simulation is not so much a question of the precision of the analog computer per se, but rather the validity of the model itself. Sometimes, supposedly linear elements may actually be non-linear in the transient sense. Consequently, a modeling approach based on the incorrect assumptions might appear satisfactory for slow phenomena but fail for fast events.

Time stepping is an inherent part of most transient computer codes. It is essential to realize that this is a fundamental restriction on the analysis technique employed. The human brain does not analyze a system by a time stepping process. Its memorized knowledge of the various response functions, and their sensitivities to various phenomena, enables it to sweep through a mass of detail and make reasonably valid conclusions about the true system performance. Needless to say this process is as much an art as a science. And moreover digital

computers up to now have found it difficult to emulate.

Laplace transformation or s variable analysis is probably the most useful tool engineers have available for treating linear systems or circuits. Unfortunately digital circuits and most radiation effects are nonlinear, and hence, this tool is not generally of help for them. The wide use of s variable analysis has acted to minimize the engineers' familiarity with time domain approaches, which is the way computer programs step through the solution. This is another reason for the dichotomy between thinking patterns and computer solution techniques.

Sensitivity analysis to a certain extent is in accord with the rough strategy the mind uses in evaluating various factors and how they affect a solution.

Radiation simulation by flash Xray, linear accelerators, lasers, reactors, Marx generators, cobalt sources, etc., has been widely used to provide radiation effects information on circuits and systems. The validity of the result depends on the pulse spectrum, time duration and shape, intensity, and secondary effects such as ground loops, shielding, input and output loading or fan in/out. For laser simulation, the presence of overlying metallizations can affect the result.

SECTION II

BASIC THEORY OF BIVARIABLE RESPONSE FUNCTION PROPAGATION

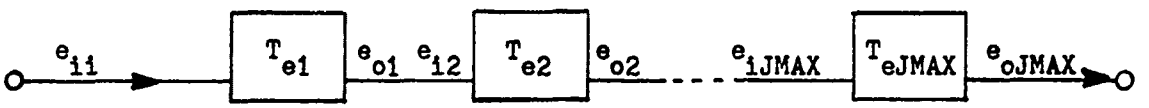
1. GENERAL PROCEDURE

As circuit and system complexity levels continue to expand, it seems to us mandatory to further develop techniques which treat circuit or system elements as blocks rather than a collection of parts. Note that this is a permissible simplification for the user compared with a designer of an integrated circuit or IC. The user of an IC can not alter the chip itself. So why should he necessarily be required to know the circuit diagram of it simply to judge its use as a block element in a more complex circuit or system? With this crucial aspect deleted from the analysis requirement, then transfer or response functions seems a permissible approach.

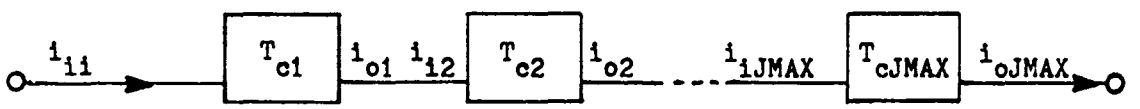
A very important consideration is that loading effects be taken into account. This immediately forbids simply treating voltage transfer functions alone. To show the elements of the general computation algorithm, let us now consider the case of simple serial blocks.

a. Serial Blocks

Suppose there are JMAX blocks connected in series with an input voltage and current applied at the input node of the first or J = 1 block, which is then propagated through it to the next so that its output voltage and current becomes the input voltage and current for the next J = 2 block, and so forth down the sequence to the last or JMAX block. Such a procedure is readily accomplished in a FORTRAN program by a DO loop on the index J.



VOLTAGE PROPAGATION CHAIN



CURRENT PROPAGATION CHAIN

The operators which yield the output given the input stimulus for a given block we will label T_e and T_c, the transfer or response functions on the voltage and current, respectively. In general, they are functions of time, and of the applied voltages and currents, as well as the circuit operating voltages, radiation degradation, etc. We will show later what some transfer functions look like, in equation and numerical form for typical circuit elements. But first the specific method for solving the system problem must be discussed.

Initially the various voltages and currents in the circuit are unknown. Thus an algorithm is needed to solve the currents for a specified input voltage and circuit configuration. To do so, note that the output voltages and currents are related to the input voltages and currents by

$$\begin{aligned} e_o &= T_{e1}\, T_{e2}\, T_{e3} \cdots T_{eJMAX}\, e_i \\ &= \left\{ \prod_{j=1}^{JMAX} T_{ej} \right\} e_i \\ &= P_e\, e_i \end{aligned} \tag{1}$$

and

$$\begin{aligned} i_o &= T_{c1}\, T_{c2}\, T_{c3} \cdots T_{cJMAX}\, i_i \\ &= P_c\, i_i \end{aligned} \tag{2}$$

where the repeated product of the block voltage and current transfer functions are abbreviated by P_e and P_c, the system response functions.

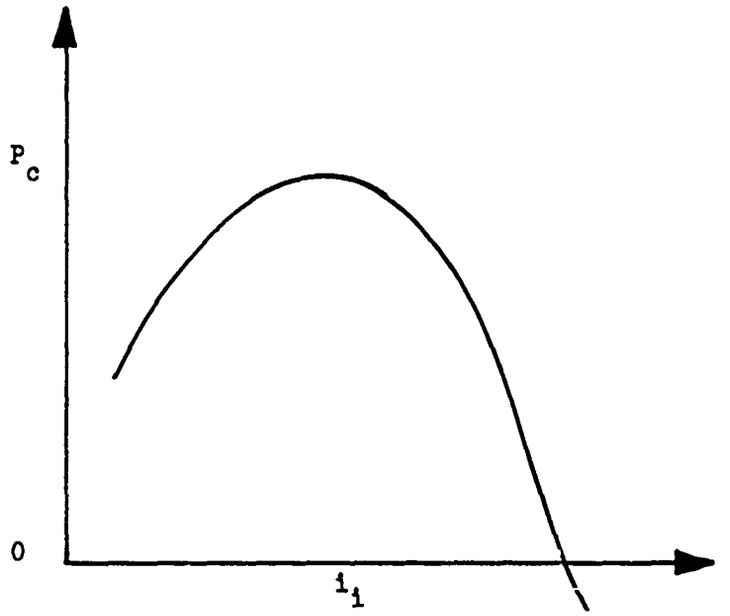
To solve the total system problem, suppose that a high-impedance load that effectively draws no current is at the last node. Hence

$$i_o = 0 \tag{3}$$

But from (2), $i_i \neq 0$, consequently the proper solution is that which drives the repeated product of the current transfer functions P to zero,

$$P_c = 0 \tag{4}$$

The system current response function is an explicit function of the input variables, and particularly the input current. Thus, if P_c is plotted versus the input current, we might have a functional dependence as shown on next page.

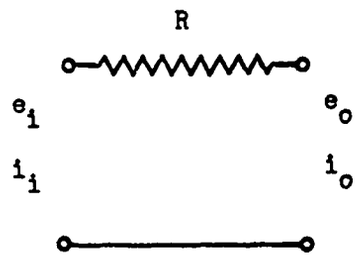


Sketch of Product of Current Transfer Functions versus Adjusted Input Variable

The computational algorithm to solve the system current and voltage problem is thus basically a zero finding process. In this case the function is regarded as a numerical form as compared with an equation or a polynomial as is the case with many system analysis techniques. The correct value of i_i is that which yields P_c equal zero.

b. Examples of Block Transfer Functions

To establish the context of thinking of simple circuit elements as block elements, consider a resistor connected in series between the input and output terminals as shown below. The output current is equal to the input current



Series Configuration

$$i_o = i_i$$

so that,

$$T_c = \frac{i_o}{i_i} = 1 \qquad (5)$$

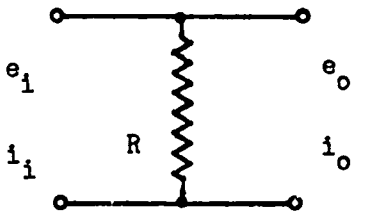
Similarly,

$$e_o = e_i - i_i R$$

hence

$$T_e = 1 - \frac{i_i R}{e_i} \qquad (6)$$

Whereas, for a shunt connected resistor, the input and output voltages are equal, but the output current is reduced by that shunted through the resistor to ground,



Shunt Configuration

$$i_o = i_i - \frac{e_i}{R}$$

so,

$$T_e = 1 \qquad (7)$$

$$T_c = 1 - \frac{e_i}{i_i R} \qquad (8)$$

Thus, the same circuit element can have different transfer functions depending on its circuit configuration. For an integrated circuit being used in a larger circuit or system the chip configuration is fixed; hence its transfer function is fixed.

The above equations for the series and shunt transfer function of a resistor are very simple analytical relations. However if we want to be able to scale complexity levels by computer analysis without completely necessitating the interaction of a skilled engineer, it pays at this point to consider an alternative mathematical representation.

Let eq. (5) for the case of a 1K ohm resistor be plotted with respect to the space of the input variables and the transfer function. It then represents a three-dimensional surface as shown in Figure 1. Suppose we are dealing with a block element for which we do not have a suitable analytical expression. By developing a numerically defined surface, and fitting it with suitable surface approximants, such as three-dimensional splines, we can still perform a system analysis. Such a surface can be deduced by experimental measurements or by operating a component level computer analysis program such as SCEPTRE and determining the response function over the space of the input variables by direct computation.

While it is certainly much more conservative of core to use an equation if that is available, we are not stopped provided we have a numerical representation of the transfer function.

To see how such a surface would be used in the computer analysis program (and actually has been in the code SAP which will be described later), a propagating DO loop brings values of input voltages and currents to a particular block, calls in the subroutines for the voltage and current transfer functions that do look-ups on the surface, and return back the value to the calling program that performs the propagation.

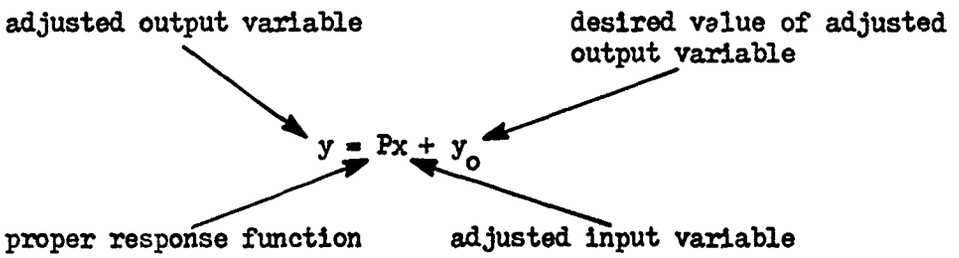
The current transfer function for the shunt connected resistor is essentially the dual of the one shown in Figure 1, with the axes being interchanged and the resistance becoming the conductance.

A list of analytical expressions for the voltage and current transfer functions for some common circuit elements is presented in Table I.

c. Iteration Algorithm

A solution of the system problem can be obtained by fixing one of the input variables, e_i, and one of the output variables, i_o. For purpose of nomenclature, let these be referred to as the fixed input or output variables. The solution strategy of the computer algorithm varies the nonfixed or adjusted input variable in a manner which forces the system current response function P_c to zero. We make an arbitrary guess at the initial value of the adjusted variable, and call it x in general, or for a specific iterate, a. This iterate is then "propagated" through the sequence of blocks.

The result of the propagation yields a value of the fixed output variable y which is probably not the desired value y_o corresponding to our constraint condition imposed (i.e. $i_o = 0$.) We need then to correct our guess at x which will bring y closer to y_o. These words can be expressed in functional form as:



(9)

Newton devised a tactic three centuries ago for solving this type of problem. Given an iterate, a , an improved guess or second iterate a' for x which drives

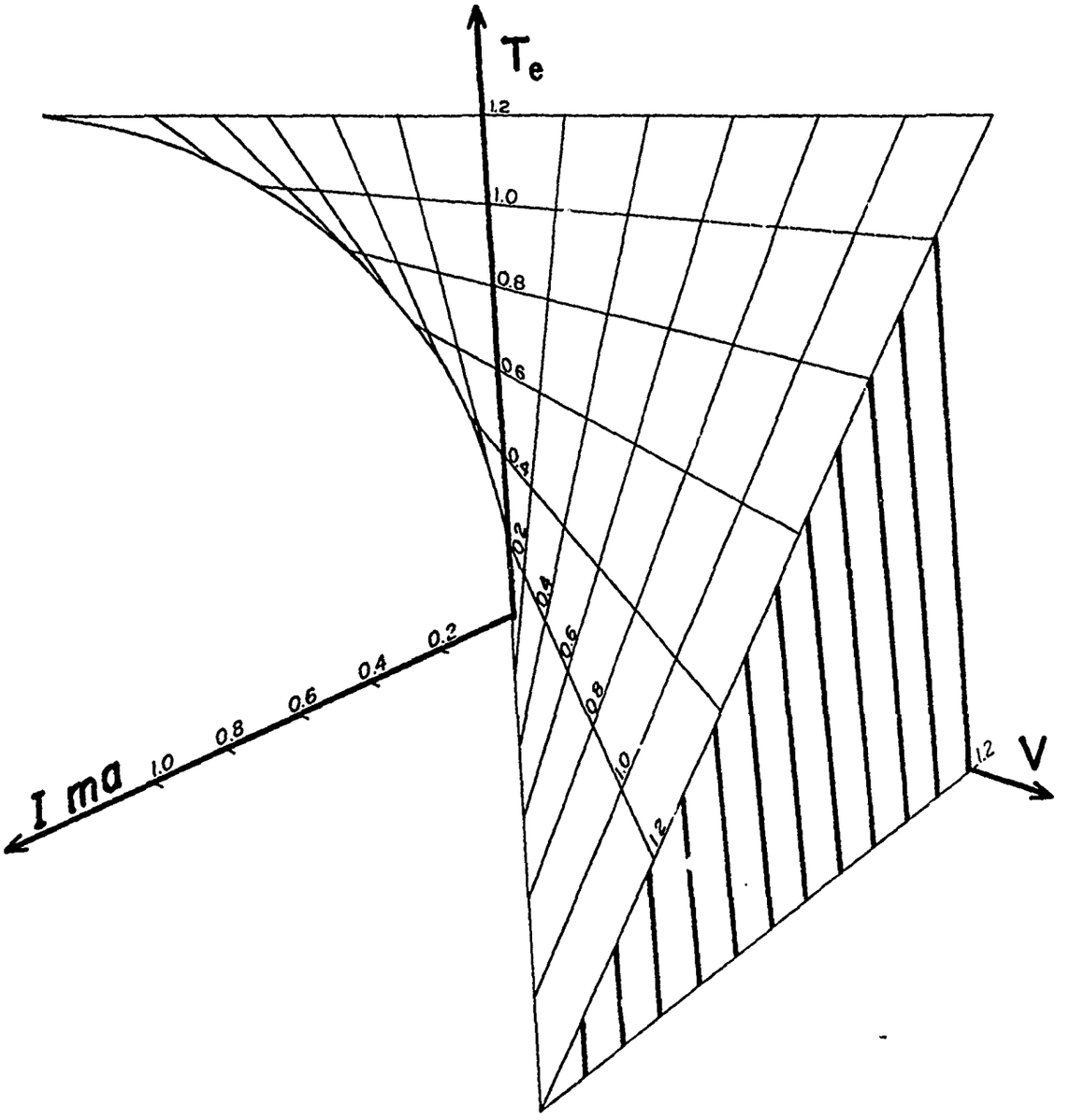
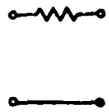
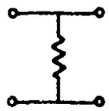
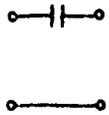
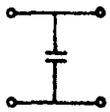
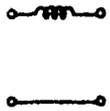
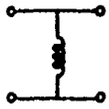
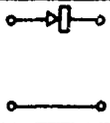
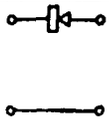
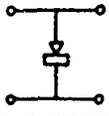
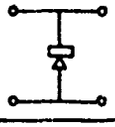


Figure 1. Voltage Transfer Function of a Series 1000 ohm Resistor

Table I

COMPONENT	CONFIGURATION	BLOCK DIAGRAMS	T_e	T_c
Resistor	Series		$1 - \frac{i_i R}{e_i}$	1
Resistor	Shunt		1	$1 - \frac{e_i}{i_i R}$
Capacitor	Series		$1 - \frac{1}{e_i C} \int i_i \, dt$	1
Capacitor	Shunt		1	$1 - \frac{C}{i_i} \frac{de_i}{dt}$
Inductance	Series		$1 - \frac{L}{e_i} \frac{di_i}{dt}$	1
Inductance	Shunt		1	$1 - \frac{1}{Li_i} \int e_i \, dt$
Diode	Series Forward Biased		$1 - \frac{kT}{qe_i} \ln\left(\frac{i_i}{i_c} + 1\right)$	1
Diode	Series Reverse Biased		$1 + \frac{kT}{qe_i} \ln\left(\frac{i_i}{i_c} + 1\right)$	1
Diode	Shunt Forward Biased		1	$1 - \frac{i_c}{i_i}\left(e^{e_i q/kT} - 1\right)$
Diode	Shunt Reverse Biased		1	$1 - \frac{i_c}{i_i}\left(e^{-e_i q/kT} - 1\right)$

y to zero, or $y - y_o$ to zero, is given by

$$a' = a - \frac{f(a)}{f'(a)} \tag{10}$$

wherein $f(a) = y$. Now since $f(a) = Px + y_o$,

$$f'(a) = \frac{dy}{dx}\Big|_{x=a} = P + a \frac{dP}{dx}\Big|_a$$

Thus

$$a' = a - \frac{(aP + y_c)}{P + a \frac{dP}{dx}\Big|_a}$$

$$= \frac{a^2 \frac{dP}{dx}\Big|_a - y_o}{P + a \frac{dP}{dx}\Big|_a} \tag{11}$$

which is the basic iteration equation utilized in the computer program SAP. It should be noted that the derivative of the response function with respect to the adjusted input variable will be of concern to the numerical solution of the problem. The numerical results which will be shown later have been calculated using eq. (11). To obtain the derivative initially, the second iterate is set at some fixed ratio of the first iterate. Typically this ratio would be $a'/a = 0.999$.

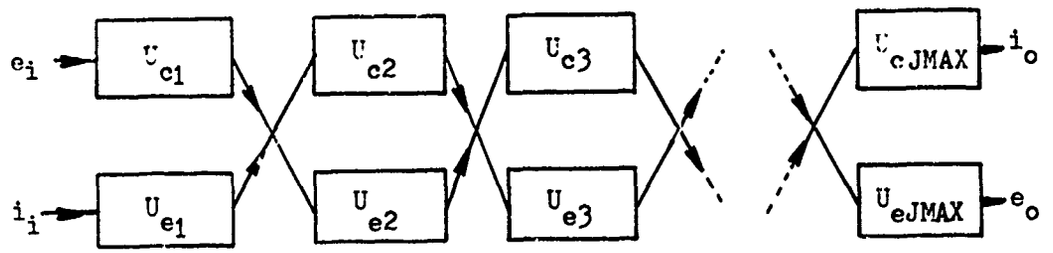
If multiple zeroes are contained in the response function, by dividing P by the first one found, the next one can be found without refinding the first one.

In a time stepping operation, the last converged value of the adjusted input variable can be extrapolated using the relative variation of the new fixed input variable compared to the last value. By this means the iteration convergence is enhanced. Using SAP for the 741 op amp, typically three to five passes are required to converge the output to 10 microvolts out of a 10-volt level. If the input impedance is linear the extrapolation may be sufficiently good to converge on the first pass.

d. Crossed Variables

In some situations the output variable which is fixed must be the same variable which is fixed in the input. In the case of the series block sequence discussed earlier, that was not the case. There the voltage was fixed at the input while the current was fixed at the output. Consequently, we could iterate on the adjusted input variable so as to drive the fixed output variable to its

proper value. It is easy to visualize this process as separate propagation of the voltage along the voltage transfer function chain, and the currents along the current transfer function chain. To help the understanding for the new 'crossed' situation, the propagation process can be looked on as cross-interacting the variables after each block as shown in the sketch below.



Mathematically eq.(9) now becomes

$$e_o = P_c^x \, i_i + e_{o,fix} \tag{12}$$

where the "voltage cross response function" is defined by

$$P_e^x = \frac{e_{oJMAX}}{i_{i1}}$$

$$= U_{e1} \, U_{c2} \, U_{e3} \, \cdots \, U_{eJMAX} \qquad \text{(for JMAX odd)} \tag{13}$$

$$= U_{e1} \, U_{c2} \, U_{e3} \, \cdots \, T_{eJMAX} \qquad \text{(for JMAX even)} \tag{14}$$

in which the Us are "cross transfer function" on the voltage or current, and are defined by

$$U_{ej} = e_{oj}/i_{ij} \tag{15}$$

$$U_{cj} = i_{oj}/e_{ij} \tag{16}$$

in which the subscript j denotes the j^{th} block. A "current cross response function" can similarly be defined as

$$P_c^x = i_{oJMAX}/e_{i1} \tag{17}$$

The equation for P_c^x is essentially the same as (13) or (14) with the e's and c's interchanged.

Previously the voltages and currents were seemingly uncoupled as the computation propagates along the blocks. Now each variable cross interacts after each block as the cross-transfer functions are called into play. While seemingly complicated, this is actually easy to incorporate in a FORTRAN program using a

sequence of computed GO TOs, or many-way switches. The remainder of the formalism is essentially unchanged and the basic iteration and convergence aspects are the same.

The cross transfer functions do not essentially introduce any new information since they are deducible from the regular transfer functions by a simple transformation, namely,

$$U_{ej} = T_{ej} \frac{e_i}{i_i} \tag{18}$$

It should be pointed out that in the course of the iteration that the ratio e_i/i_i is not the input impedance of the block in the general sense. Rather we are using the voltages and currents as independent variables. Only after the solution has converged correctly as demanded by the constraint of eq.(4) does the e_i/i_i ratio represent the physically correct input impedance as seen at that block element.

Thus, the iteration process can be looked upon as finding numerically that coupling of the voltage and current variables which correctly satisfies the physical problem.

e. Parallel Blocks

So far the circuit or system has been treated as a sequence of blocks connected in series. The computational algorithm is a DO loop that simply propagates the current and voltage variables from J = 1 to J = JMAX. This DO is nested in the outer iteration DO which acts upon the adjusted input variable. Suppose now that a number N of blocks are connected in parallel, presumably located in the previous series sequence. Let us now see if we can devise an effective algorithm for solving this problem by a transfer function method.

Presume that the input current in branch j is some fraction F_j of the total available input current, and that on the first iteration pass the current is assumed to split equally, so that $F_j(1) = 1/N$. The current into the j^{th} block is then

$$i_{ij} = F_j(1)\, i_i \tag{19}$$

Knowing these input currents and the value of the input voltage, the output voltage calculated using their voltage cross transfer functions U_{ej} as given by (15), can be used to calculate the <u>average</u> output voltage of all the parallel blocks as

$$\bar{e}_o = \frac{1}{N} \sum_{j=1}^{N} U_{ej}\, i_{ij} \tag{20}$$

and the deviation of the individual blocks from that computed average,

$$\Delta e_j = e_{oj} - \bar{e}_o \tag{21}$$

Next a relation indicating how a block output voltage can be related to a change in block input current is obtainable by differentiating eq.(15), yielding

$$\Delta e_j = U_{ej} + i_{ij} \frac{\partial U_{ej}}{\partial i_{ij}} \Delta i_{ij} \tag{22}$$

By equating the left hand side of (22) to the deviation (21) incurred on a given iteration pass, the change in the current which should be propagated through a block in order to drive it closer to the average is then obtained from (22). However, if all the new input currents are calculated in this manner, it would seem unlikely that their sum would still equal the available input current i_i coming from the prior block in the series sequence. Suppose that the sum of the new input currents obtained using the increments calculated from (21) and (22) is

$$i_i' = \sum_{j=1}^{N} i_{ij} \tag{23}$$

and that the ratio of this sum to the available input current i_i is some fraction f,

$$f = \frac{i_i'}{i_i} \tag{24}$$

If all the tentative block input currents are divided by f, then Kirchoff's current law at the input node is again satisfied. These new input currents are then propagated through their blocks and a new floating average output voltage is computed as before, and the whole cycle is repeated until $\Delta e_j = 0$.

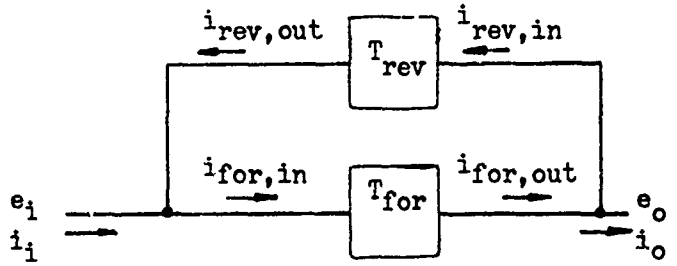
It is important to note that the above algorithm retains the advantages of the sequential analysis, namely:

- complete symmetry in the computational sense with respect to all block elements,
- no necessary restrictions to linearity, and
- no matrices involved in the solution.

The parallel block algorithm is a generalization on Newton's method where the fixed output constraint is changed to convergence to an average output voltage which floats during the iteration process.

f. Feedback Loops

Up to now the blocks have been considered as propagating input variables in one directed sense from the input node to the output node of the circuit or system. In this subsection a feedback loop will be considered with the transfer functions presumed to have a directionality. Surprisingly, the voltage transfer functions are **not** equal in this case, as was true for the simple parallel case.



Rather since

$$e_o = T_{e,for}\, e_i$$

and

$$e_i = T_{e,rev}\, e_o$$

the result is

$$T_{e,for} = \frac{1}{T_{e,rev}} \qquad (25)$$

The computational algorithm for this case is somewhat like the parallel case described previously. To initiate the calculation apply e_o and some fraction of i_o to the reverse block and propagate to find $e_{rev,out}$ and $i_{rev,out}$. Next define

$$\Delta e = e_{rev,out} - e_i \qquad (26)$$

Use Kirchoff's law and set

$$i_{for,in} = i_i + i_{rev,out}$$

Calculate a new e_o using the voltage cross transfer function, and $i_{for,out}$ using the current direct transfer function for the forward block. The voltage out of the reverse block is

$$e_{rev,out} = U_{e,rev}\, i_{in}$$

This equation for the voltage out of the feedback block can be differentiated to yield

$$\Delta e_{rev,out} = \left\{ U_{e,rev} + i_{rev,in} \frac{\partial U_{e,rev}}{\partial i_{rev,in}} \right\} \Delta i_{rev,in} \qquad (27)$$

Equation (27) can then be solved for the new value of $\Delta i_{rev,in}$ using the prior value of Δe which will drive the voltage difference Δe toward zero. The condition $\Delta e = 0$ corresponds to the desired result, since Kirchoff's voltage law is then obeyed. The above process is recycled until that condition is obtained.

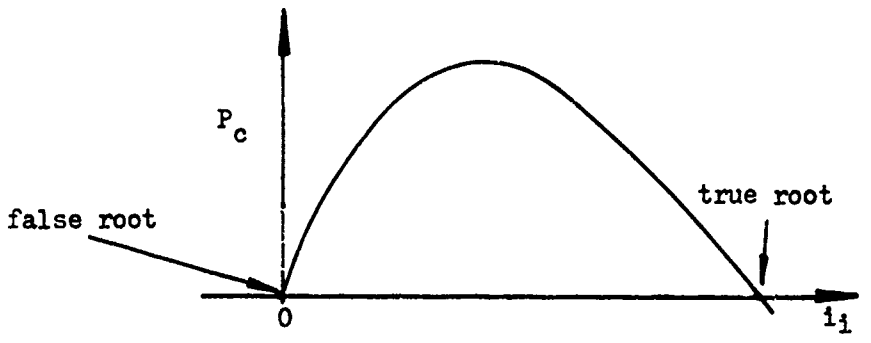
g. False Zeroes

The basic condition used in this iterative method for solving the total system aspect of the problem is that the repeated product of the block transfer functions, P_c , drives to zero when the output constraint is properly satisfied. Normally this will happen when

$$T_{c,JMAX} = 0 \tag{28}$$

For linear circuits no problem will arise if, during the iteration process, an iterate drives the block into an extreme condition. If the block is non-linear the same statement can not in general be made. As a result an intermediate T_{cj} may drive to a false zero. There may be physical cases when this might occur validly. However, before the iteration process is completed the variables are uncoupled and the zero is improper. In such a case, logic must be used in the block subroutine to check whether such is the case, and if so alter the value propagated on to a satisfactory non-zero value. Generally the logic condition we use in this test is that only the last block has a normal zero value of the output current when the input to the block is non-zero.

A more typical false zero arises from the fact that there is an automatic zero of the P function if the input current to the first block, CIN(1), is driven to zero by the iteration process. In other words, the function P has at least one false and one true zero for a given value of the fixed input variable. Such a condition is shown in the following sketch.



Thus, the iteration driver routine needs to have more sophisticated zero finding strategies than a simple Newton-Raphson method which steers the iterate only on the basis of the derivative. Bounds must be set to restrict the iteration from driving to the false zero. The P function must also be free of other anomalies such as wild derivative variations in the neighborhood of the root; and if

the bounding technique is to work, free also of sliding of the root with the iterate as the iteration process homes in on the final value.

2. NONLINEAR RESPONSE FUNCTIONS

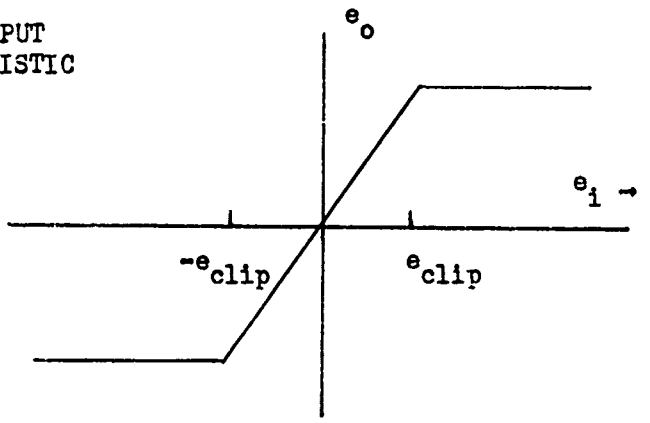
In this section we will get into the heart of modeling problems relating to nonlinear, complex, circuits. The prior section has shown that using ideas such as bivariable propagation, specific algorithms can be devised which correctly solve the case of circuits consisting of interdependent blocks. This is essential if loading effects such as fan-in and fan-out are to be properly taken into account. Thus, we can affirmatively say that it is at least permissable to consider using transfer or response functions for the block elements and still be able to perform valid system analysis. The prime questions which yet remain to be answered relate to the ability to properly take into account general classes of nonlinearities. The results obtained so far are encouraging as the results presented will show.

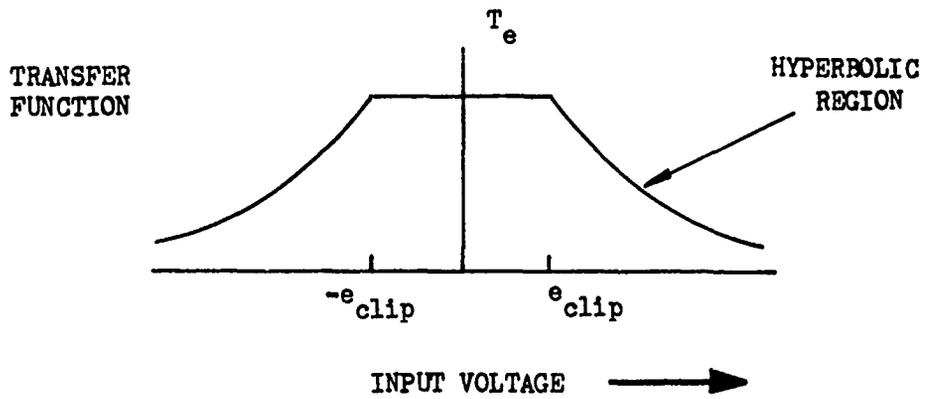
a. The 709 and 741 Operational Amplifiers

To provide an understanding of the applicability of the prior formalism to nonlinear blocks, two operational amplifiers will be treated and compared with one another to see the universality and the differences which accrue to separate devices. The 709 is an externally compensated monolithic integrated circuit op amp with a low-frequency gain of about 25,000. It is reasonably linear over a range of plus and minus 400 μv, and then saturates hard. The 741 is similar to the 709, with a somewhat higher low-frequency gain of 28,000; the prime difference between the two is that the 741 contains its own compensation circuit, and has internal balance points for offset adjustment. Neither the 709 nor the 741 are radiation hardened.

The general type of nonlinearity which these op amps have is shown in the following sketches.

INPUT-OUTPUT
CHARACTERISTIC





Let the input voltage at which the device starts to clip hard be referred to as e_{clip}. The corresponding transfer function T_e then has the form shown above. The voltage gain is constant over the linear range. Outside that range, the output is constant while the input continues to increase, thus the voltage transfer function has the form of a constant divided by an independent variable, the equation of a hyperbola. Hence, beyond e_{clip} the transfer function is a segment of a hyperbolic sheet. This is the mode of presentation of saturation class of nonlinearities as it is usually presented in the textbooks. There is much more to it than that.

To determine the time domain transfer functions, a step pulse was applied to the input, and the resultant response of the device photographed on an oscilloscope. By varying the magnitude of the step height, the time domain "turn on" transfer functions shown in Figure 2 for the 709 and Figure 3 for the 741 were determined. The height of the transfer function when multiplied by the magnitude of the pulse step indicates directly the time development of the output waveform. The shape of the 709 surface has some interesting surprises.

A time delay or propagation delay is evident for very small pulse amplitudes that gives rise to a valley in the supposedly linear range of the 709 device characteristic. This valley persists for up to 18 ms after device turn on. Note that the T_e surface for the 741 does not show this effect. Three important conclusions are:

1. the above result shows that nominally linear devices can be nonlinear in the transient sense,
2. the boundary region between linear and nonlinear modes of operation is not constant at a value of input voltage

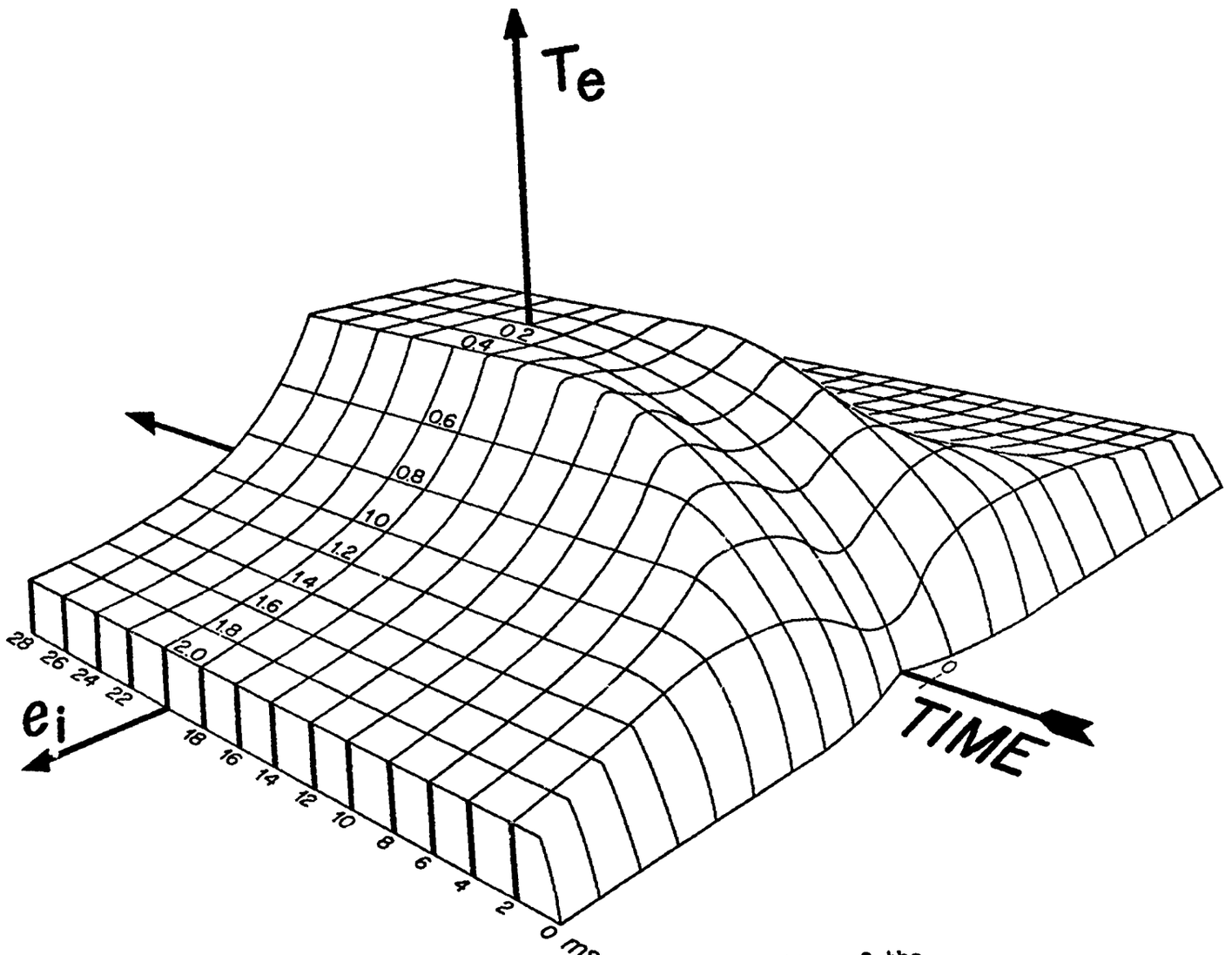


Figure 2. Time Domain Voltage Transfer Function of the 709 Op Amp, Response to Voltage Step Turn-on

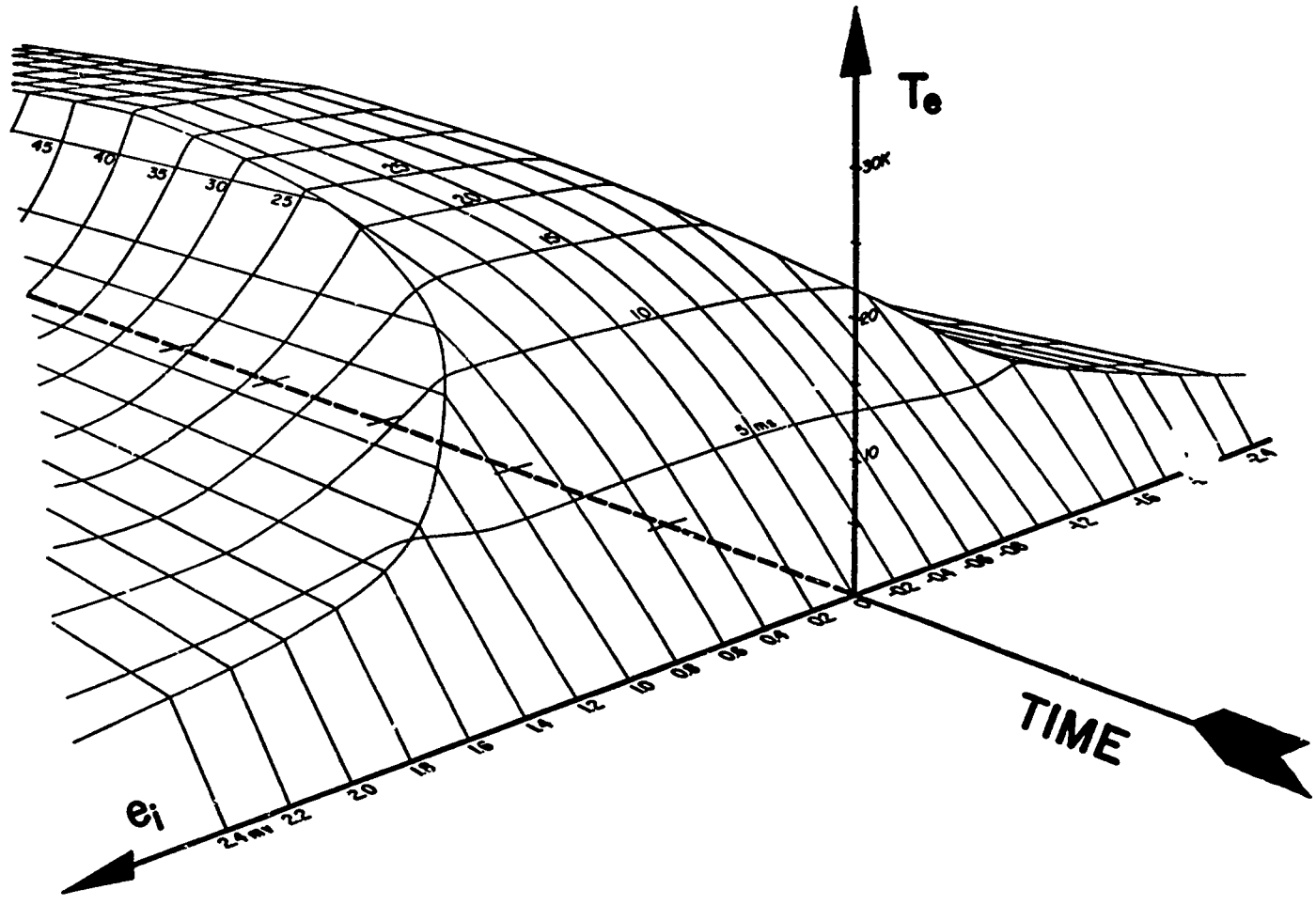


Figure 3. Time Domain Voltage Transfer Function of the 741 Op Amp, Response to Voltage Step Turn-on

e_{clip} but rather swings out to higher input voltages at early values of time. Roughly the shape of this transition region is hyperbolic in the (e_i,t) plane,

3. the step transfer function rises up to a maximum value and remains flat or constant at long periods of time after step turn on.

It is clear by inspection of the time domain transfer function that a far more meaningful understanding of the device characteristics is obtainable from it than from the simple DC input-output characteristic. The physical sense of inertia is obvious. Hit the device with a stimulus and it takes up to 50 ms for the 741 to respond. This is the obvious cause of phase shift in the device. Also we see that the harder we hit the device (which corresponds to moving out further along the e_i axis), the faster the device responds. It does not respond any harder once the nonlinear range is reached, but it does respond faster and faster until the response is slew-rate limited and thereafter the rise is constant.

While this surface was obtained by experimental observation of the device response on an oscilloscope and plotting the results using perspective drawing techniques, such a surface could have been equally well obtained by using a component level analysis computer program such as SCEPTRE. Three-dimensional computer plotting routines can generate a perspective plot rather easily. The most important question that must be asked is whether or not such a surface is of use in performing transient analysis at higher complexity levels. If so, then we have a strictly numerical way of staging complexity levels in system analysis. Our results for the combination of electrical and radiation stimuli on the 741 are encouraging.

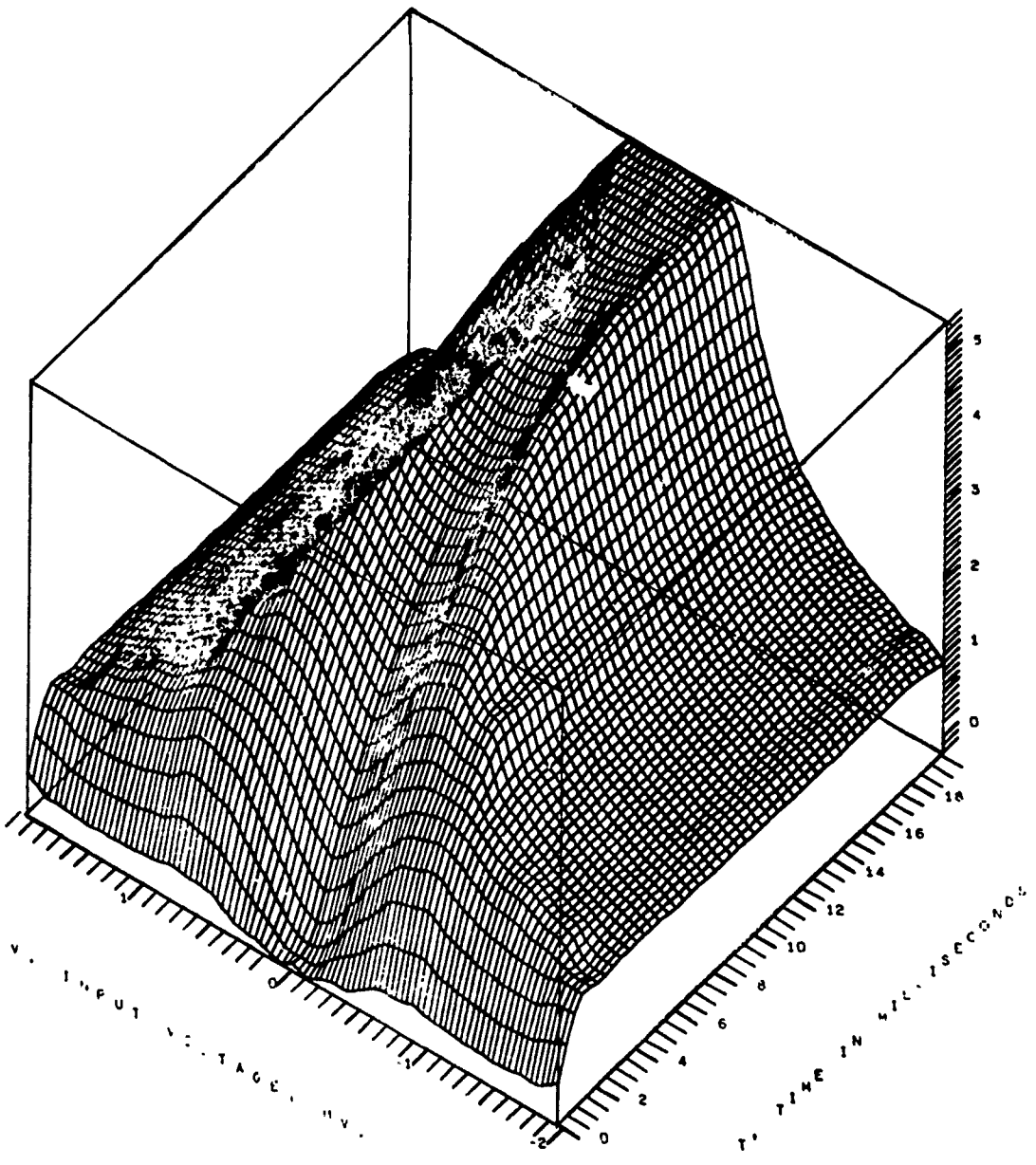
A computer generated approximation to the experimental surfaces are shown in Figures 4 and 5. This approximation uses three-dimensional splines fit in the least square sense.

The time domain response function of the 709 demonstrates quite nicely three general types of nonlinearity:

- saturation or clipping,
- distortion, and
- propagation delay.

There are other classes of nonlinearity which Figure 2 does not show, namely,

- storage,



S-FF RESPONSE FUNCTION SURFACE OF INTEGRATED CIRCUIT 709 OP AMP

Figure 4. Time Domain Voltage Transfer Function of the 709 IC Op Amp Response to Step Pulse Turn-On

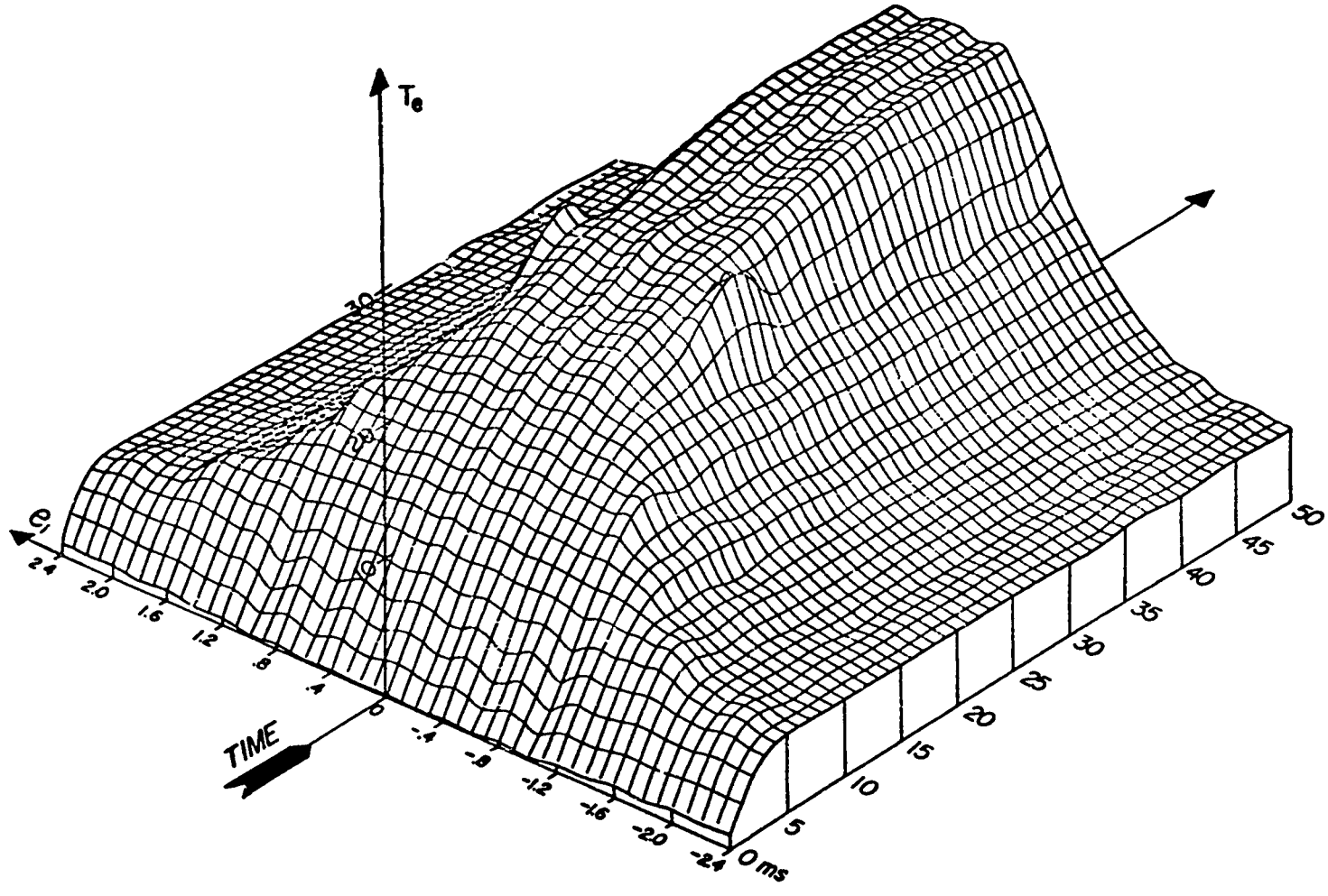


Figure 5. Computer Generated Three Dimensional Computer Plot of the Step Pulse Voltage Transfer Function of the 741 Op Amp. This plot is the result of the first pass at a computer fit and should be compared with that shown in Figure 20.

- deadzone,
- hysteresis, and
- instabilities, such as latch-up.

Of these four, deadzone is very easy to model since that simply is represented by a region in the three dimensional surface where the vertical height T is zero. Storage will be discussed in detail as it applies to the 709. Hysteresis is not a major effect with the 709 but could be for some digital circuits, such as a Schmitt trigger. Latch-up is a serious instability induced in semiconductor integrated circuits by radiation. It is generally a form of positive feedback in the internal circuit permitted to happen as the isolation junction to the substrate becomes conductive due to the photocurrent.

b. Storage Time Surface of the 709

The transfer function surface given in Figures 2 and 3 were obtained by photographing the response to a pulse as presented on an oscilloscope. A typical waveform is shown in Figure 6. The input pulse is in the linear range.

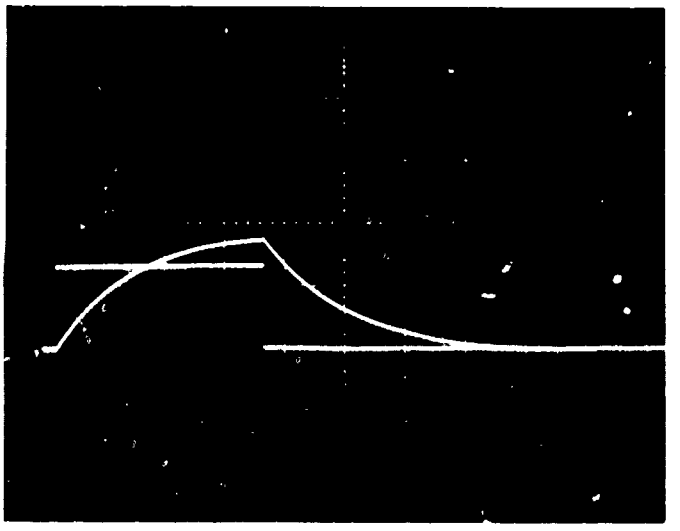


Figure 6. Polaroid Oscilloscope Photograph of Input and Output Voltage Waveforms of 709 Op Amp

The important point to note is that the output immediately starts to drop as the pulse turns off. In other words there is no storage in the linear range.

The surface as given in Figure 2 represents the rising part of the output waveform. In the linear region, it is seen that the falling part is the same as the rising.

When the input signal drives into the nonlinear range, the output signal quickly rises to the maximum allowable swing, 13 v, and clips hard. When the input is turned off, the output holds up at the same maximum value for some time, which we will term the storage time, τ_s, after that turnoff. Then the output drops with the same shape that it fell in the linear range. This aspect of the device characteristic is not contained in the turn-on transfer function surface of Figure 2.

The length of time that the output remains up after turn off of the input drive increases as

- the magnitude of the drive pulse increases,
- the length of the drive pulse increases,

up to a maximum value of storage time.

By experimentally observing the correlation of the storage time with the pulse amplitude and length, the three-dimensional surface presented in Figure 7 was determined.

The horizontal axis of the three-dimensional drawing is the magnitude of the electrical input signal applied to the inverting input of the 709 operational amplifier, the axis running backward is the pulse length in milliseconds applied to the input, while the vertical axis is the storage time in milliseconds.

The drawing itself was initially prepared using three point perspective grids approximately 3 feet square. It is necessary to use such large grids in the initial drawing in order to retain any semblence of the precision inherent in the data. The use of the grids is nicely described in the book by McCartney*.

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*T. O. McCartney, Precision Perspective Drawing, McGraw-Hill Book Company, New York, 1963. The grids are obtainable from Perspective, Inc., 4400 Seventh Avenue, Seattle, Washington.

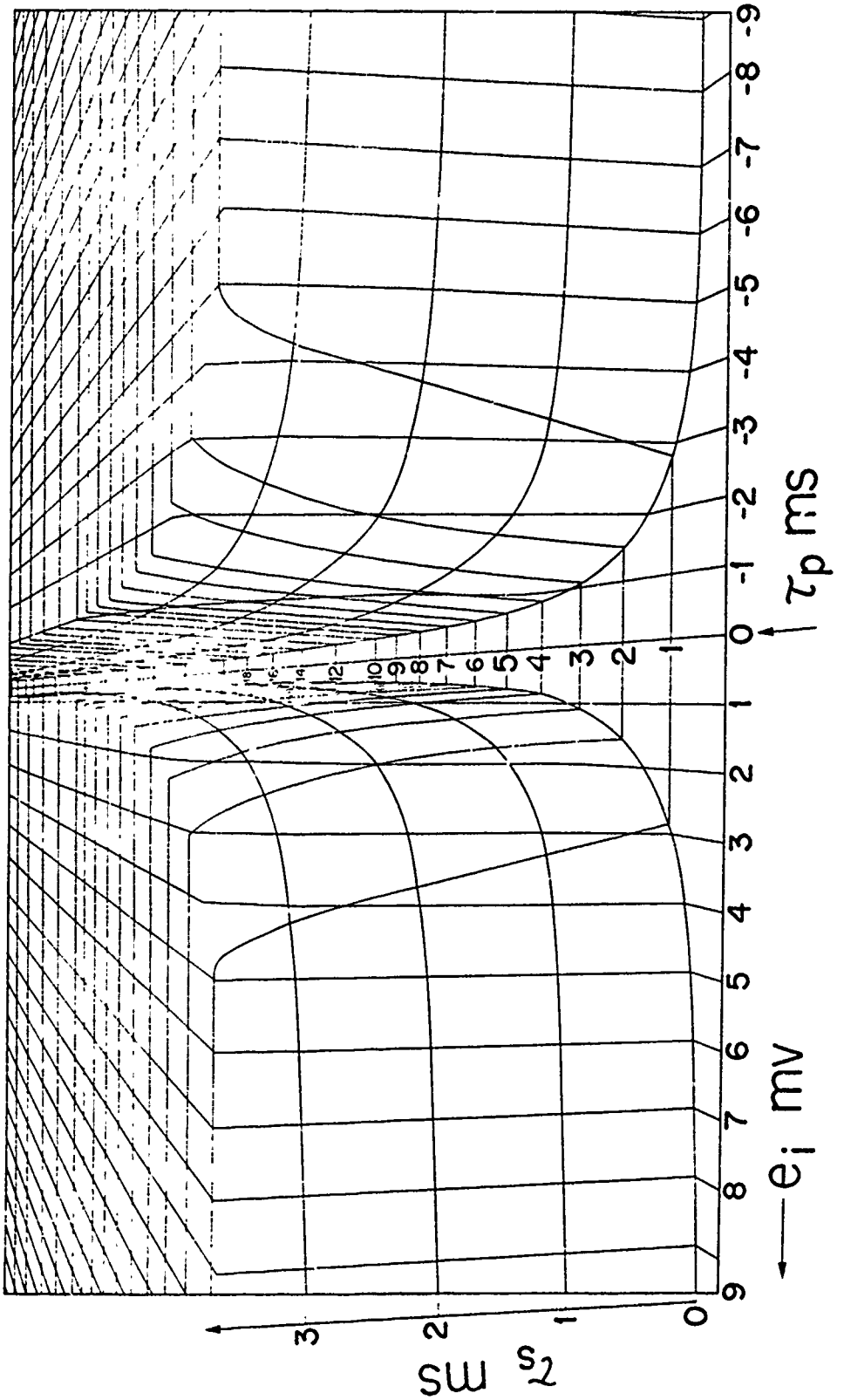


Figure 7. Storage Time Surface of the 709 Integrated Circuit Op Amp

Figure 7 presents at a glance the dependence on the input voltage e_i and pulse length τ_p of the storage time τ_s. The especially interesting things to note at this point are:

- for short pulses, large signals can be applied without storage resulting,
- for long pulses, only a small excursion beyond the linear range results in maximum storage,
- the roughly hyperbolic shape of the iso-storage curves or cuts through the surface parallel to the (e_i, τ_p) plane.

The first point is of theoretical importance since it relates to the equivalence of step pulse and impulse analysis of a circuit.

The storage time obtained from the storage time surface is actually used in conjunction with what we will term the "turn off response surface," a surface representing the decay characteristic of the output waveform after pulse turnoff. This surface is represented in Figure 8. The surface has three essential zones:

- exponential cylindrical - the linear decay region,
- hyperbolic cylindrical - the region where the pulse continues out to the storage time τ_s at full amplitude before starting to drop, and
- hyperbolic exponential - the drop from saturation for input stimuli exceeding the linear range.

The information obtained from Figure 7 is utilized in the computer program SAP to locate the line of demarcation between the hyperbolic cylindrical and the hyperbolic exponential zones. In other words, that line of demarcation is a moving line rather than a fixed unchanging line for a given input pulse. The particular location given in Figure 8 corresponds approximately to the case of maximum storage time at the signal level $e_i = 2$ mv. At a signal level $e_i = 0.8$ mv it is seen that the storage time $\tau_s = 2$ ms. Then by inspection, a storage time of $\tau_s = 2$ ms corresponds to a pulse length $\tau_p = 4$ ms. Thus the turn off response surface has been drawn for the case of an input pulse 4 ms long. What the computer look-up on the the storage time surface does is provide a displacement of the line of demarcation to the proper position corresponding to the particular applied waveform. The degree of success obtained by this technique is shown later in the computer output waveforms of Figure 11.

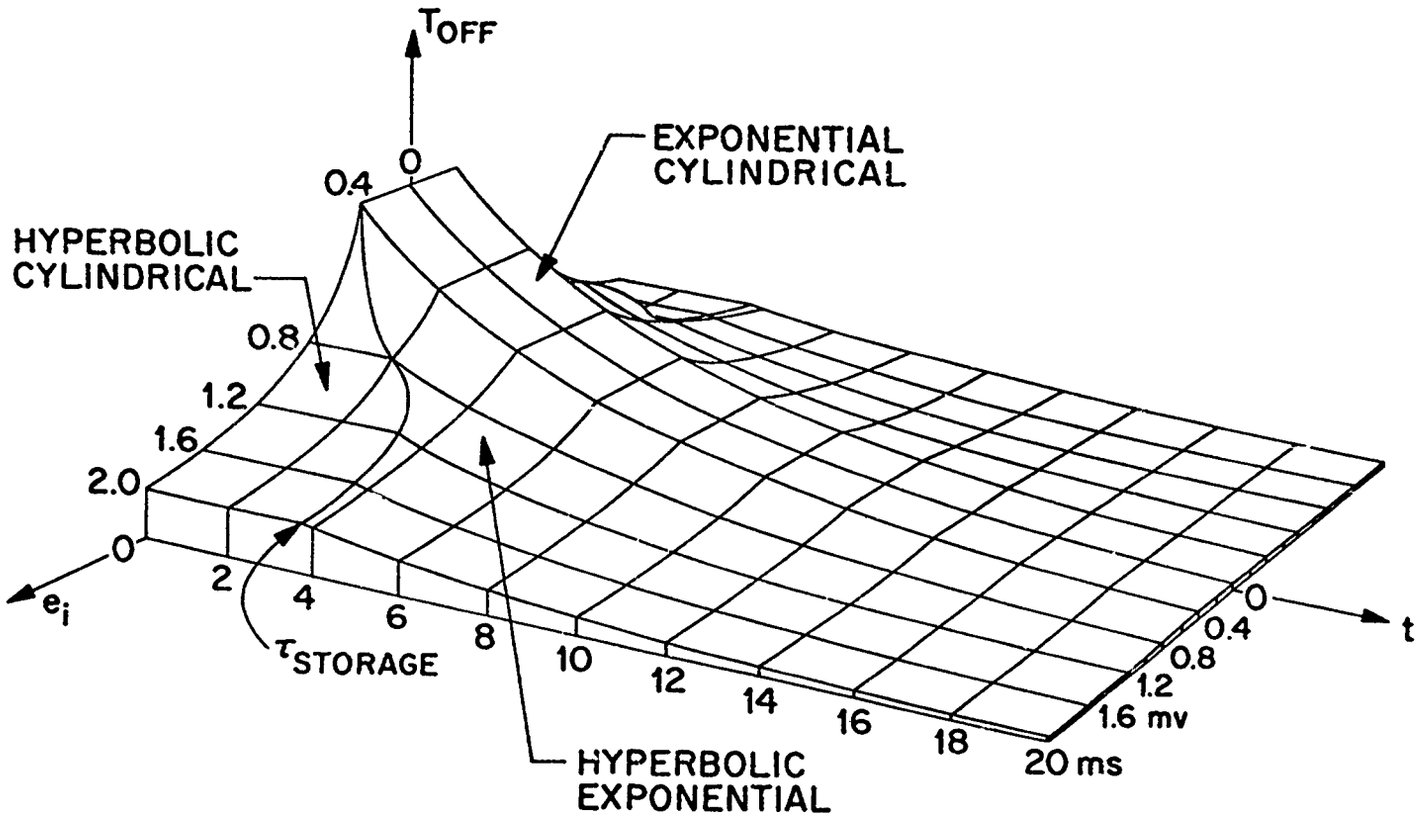


Figure 8. 709 Turn Off Response Surface

c. Artificial Terms in Transfer Functions

One attribute of the bivariable propagation technique that might not be obvious is that it requires a functional dependence of the output variable on the input variable. This is needed to steer the iteration process which drives the adjusted input variable to the proper value determined by the total system configuration. Now for digital circuits, the output is constant over a wide range of variation of the input voltage, such that a plot of P_c, the total system current response function, might be expected to have regions which are essentially parallel to the adjusted input variable axis. Consequently a Newton's method extrapolation to the next iterate would not operate. A linear interpolation method might be satisfactory since it can broaden the search range.

Another way to proceed shows unexpected and extremely important useful, and in fact mandatory, aspects of our time domain transient calculations using iteration on a time stepping basis with transfer functions.

(1) Current Transfer Functions

Up to now only surfaces or drawings showing the voltage transfer function have been presented. Yet the bivariable propagation method also needs current transfer functions. The current transfer function holds the key to establishing a satisfactory iteration convergence mechanism. A first guess at an output current would set $i_o = e_o/R_L$, where e_o is the output voltage established by T_e, the voltage transfer function, and R_L is the load resistance. For the sake of simplicity of the argument, suppose that the transition process of a flip-flop does not depend on e_i. In that case

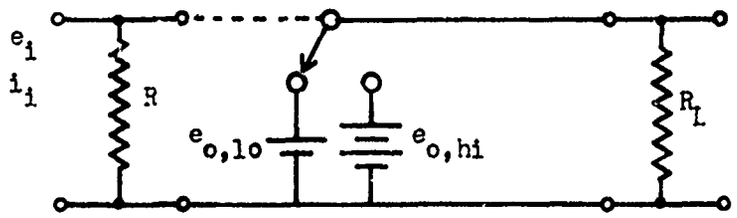
$$T_c = \frac{i_o}{i_i} = \frac{T_e e_o}{i_i R_L}$$

where

$$T_e = \frac{e_{o,hi}}{e_i} \quad \text{or} \quad T_e = \frac{e_{o,lo}}{e_i}$$

However, now there is no explicit dependence of the output variables on any change of the input variables except for the high-low transition. As a remedy, presume that the flip-flop has an input resistance R, and that we think of it as an external shunt resistor block. Connect the output node of the input resistor to the output node of the flip-flop by a dotted line that passes current but not

voltage. Then if the new value of i_i is not the correct value the given input voltage e_i and the resistor R, the current difference Δi will pass the shunt



resistor into the flip-flop and the output so that the output current is

$$i_o = \Delta i + \frac{e_o}{R_L} \tag{29}$$

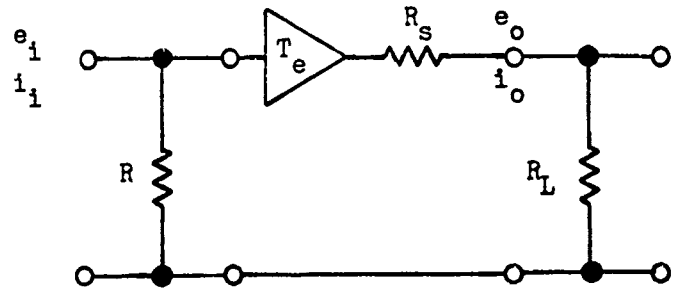
This is not the correct current physically unless $\Delta i = 0$. However, the output current does now depend explicitly on the input current, and hence, the bivariable propagation and iteration procedure can again operate regarding current as the adjusted input variable. If we imagine the constraint to be a high-impedance voltmeter connected across R_L, then the iteration process will drive the error current Δi to zero. Then the current transfer function is the physically correct transfer function for the flip-flop, and the correct current feeds the load resistor. Thus the transfer functions may contain an artificial component to assist numerical convergence so long as that term drives to zero when the correct solution is obtained.

(2) Dynamical Delay

Here let us explore one further crucial but not obvious aspect of trying to iterate around a block element containing dynamical time delay. Suppose that an input stimulus is applied and that the correct coupling of the input variables has not yet been obtained. For example, suppose that an input voltage within the linear range of the 741 op amp is applied. By inspection of Figure 3, the T_e surface, it is evident that a significant time passes before the output responds to the stimulus. This time may be several milliseconds. Suppose that the time step interval is say a fraction of a millisecond. Then many time steps pass before the output or condition of the circuit has been changed by the iteration process at the input of the device. How then can the basic iteration process work?

We believe the answer again lies in the use of two rather than one chain of transfer functions to propagate information. For the case of the op amps,

the current transfer function is obtained using a similar procedure to that used above for the flip-flop. An input resistor R acts as a shunt block element. The T_e transfer function provides the gain and the dynamics, and a source impedance R_s is in series with the load resistance R_L.



Suppose that the iteration process has not yet provided the correct coupling of the input variables to the block. Then an error current Δi as before will drive past the input resistor, through the gain element, and through to the output. Thus, the output current is as before

$$i_o = \Delta i + \frac{e_o}{R_s + R_L} \tag{30}$$

where

$$\Delta i = i_i - \frac{e_i}{R} \tag{31}$$

and

$$e_o = T_e\, e_i$$

The key result is contained in (30) since the second term contains the block dynamics from the time domain transfer function surface and is delayed properly; however, the error current Δi is not delayed and propagates immediately through the block and steers the iteration process.

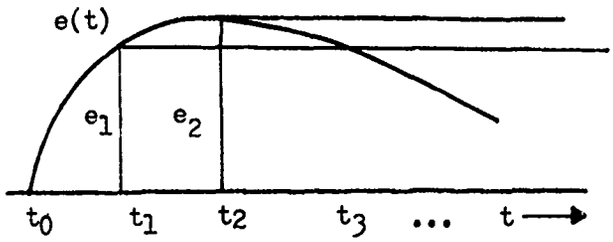
3. INPUT WAVEFORM DECOMPOSITION AND OUTPUT SUPERPOSITION

The major problem relating to nonlinear system analysis is loss of the validity of the principle of superposition. Yet as we will show shortly, it is possible to obtain reasonably accurate results using the type of nonlinear time domain transfer functions presented earlier for certain classes of nonlinearity. For other types of nonlinearities, the results are less accurate.

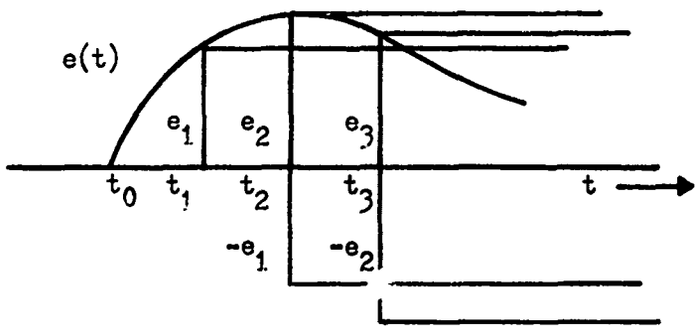
a. Step Pulse Decomposition

Let an arbitrary waveform e(t) be applied to a block. Suppose that the

time stepping of the computer program samples that waveform at times t_0, t_1, t_2, etc., obtaining voltages e_0, e_1, e_2, etc. If just a step pulse of magnitude e_1 say had been applied, then the output at subsequent time steps could be obtained directly from the time domain transfer function surface T_e by evaluating its value at time increments measured from time of turn-on t_1 and multiplying that by the



magnitude of the step e_1. Then the same procedure could be followed for the next step pulse e_2 and so forth. To prevent overdriving the input, since the earlier step would also be on, it is necessary to turn off step e_1 at the next time step t_2. This is done be applying the turn-on of the negative e_1, and add its response to the output. The decomposition of the input waveform would look as sketched below.



Taking $e_0 = 0$, the output at time step t_2 would be

$$e_o(t_2) = T_e(e_1, t_2-t_1)\, e_1 - T_e(e_1, t_2-t_2)\, e_1 + T_e(e_2, t_2-t_2)\, e_2$$

Similarly at time step t_3,

$$e_o(t_3) = T_e(e_1, t_3-t_1)\, e_1 - T_e(e_1, t_3-t_2)\, e_1 + T_e(e_2, t_3-t_2)\, e_2 - T_e(e_2, t_3-t_2)\, e_2 + T_e(e_3, t_3-t_3)\, e_3 \qquad (32)$$

By inspection of the T_e surface for the 709 or the 741, it is seen that at time zero the vertical height is zero. Thus, the last term in (32) is zero, or at least very small. Further, it can be seen that the other terms in (32) have the input voltage at one time step multiplying the difference in the value of the transfer function evaluated one time step apart. That, however, is just the value of the time derivative of the transfer function surface evaluated at the value of the input voltage and the time since step turn on, multiplied by the magnitude of the time step. Hence, (32) becomes

$$e_o(t_3) = e_1 \left.\frac{\partial T_e}{\partial t}\right|_{e_1, t_3 - t_1} dt + e_2 \left.\frac{\partial T_e}{\partial t}\right|_{e_2, t_3 - t_2} dt \qquad (33)$$

Or, passing to the general case,

$$e_o(t) = \sum_{j}^{J} e_j \left.\frac{\partial T_e}{\partial t}\right|_{e_j, (J-j)dt} dt \qquad (34)$$

where J is the latest time step index value. Equation (34) is the basic form of the convolution principle or the principle of superposition which has been used in the program SAP to compute the output waveforms which will be presented herein.

While the above mathematics is mandatory in order to perform a computer analysis, it does not give us any direct insight into what is happening on the transfer function surface. It is not difficult to obtain an understanding using that surface which is very helpful in treating transient problems.

Suppose (34) is interpreted in terms of either the 709 or the 741 voltage transfer function surface, Figure 2 or 3. Let the first pulse decomposition element e_1 be referred to as a partition. Then the output in time following its turn on is mentally visualized by coming out laterally on the e_i axis to the value of input voltage e_1 and then imagining the partition moving on isovoltage portion of the surface forward in time parallel to the time axis. That partition continues to contribute to the output until it reaches the portion of the surface where the time derivative of the surface goes to zero.

The next partition moves back along that isovoltage part of the surface corresponding to e_2 and again contributes until the time derivative of that part of the surface vanishes. Convolution is just the continual running summation of successive partitions contributions to the output. Such a process is theoretically justifiable only for linear elements.

b. Computed Results for the 709 and the 741

With the last statement firmly in mind, let us now examine some reults. First with a 1.0 mv step pulse applied, and using 0.1 ms time steps, the computed output voltage is shown in Figure 9. The input waveform is shown in the top half, and the computed output in the bottom half. From the figure it is immediately evident that superposition can be used with reasonably good validity for saturation class of nonlinearities.

To most easily understand the way the constant output limit is achieved in the calculation, think how the partitions moving back along isovoltage trajectories on the T_e surface contribute to the output. By inspection of the surface in Figure 2, it is seen that for $e_i = 1.0$ mv it takes about 4 ms for the output to saturate and for $\dot{T}_e \to 0$. The input waveform in Figure 9 is not a step but takes about 1 ms to turn on. The partitions for $0 \leq e_i \leq 1.0$ mv travel along the valley portion of the surface. Those in the linear range contribute for as long as 20 ms from time zero. The partitions above the linear range contribute for shorter time intervals. The reason the output holds up at a nice, relatively constant value is that as the first partitions reach the flat hyperbolic sheet and cease to contribute, the fact that the waveform is till turned on means that subsequent partitions are starting to climb up the surface thereby maintaining the output constant in the steady state.

The variation in the output voltage in Figure 9 is about $\frac{1}{2}$ v in 10 v; thus the superposition principle as applied using (34) is valid to 5% for this case.

c. Computation of Storage Effects

Earlier the fact that storage phenomena are not included in a turn on surface, led to the portrayal of the storage time surface and the turn off surface in Figures 7 and 8 for the 709 op amp. Here, the way this is taken into account relevant to the superposition tactics of eq.(34) will be presented.

Suppose that a waveform is applied which drives into the nonlinear range above the input clipping voltage e_{clip}. As before pulse decomposition is applied and a sequence of partitions travels up the turn on surface. Now however when the waveform turns off, logic in the computer program determines how long the voltage had held up at the levels corresponding to the values at which the partitions

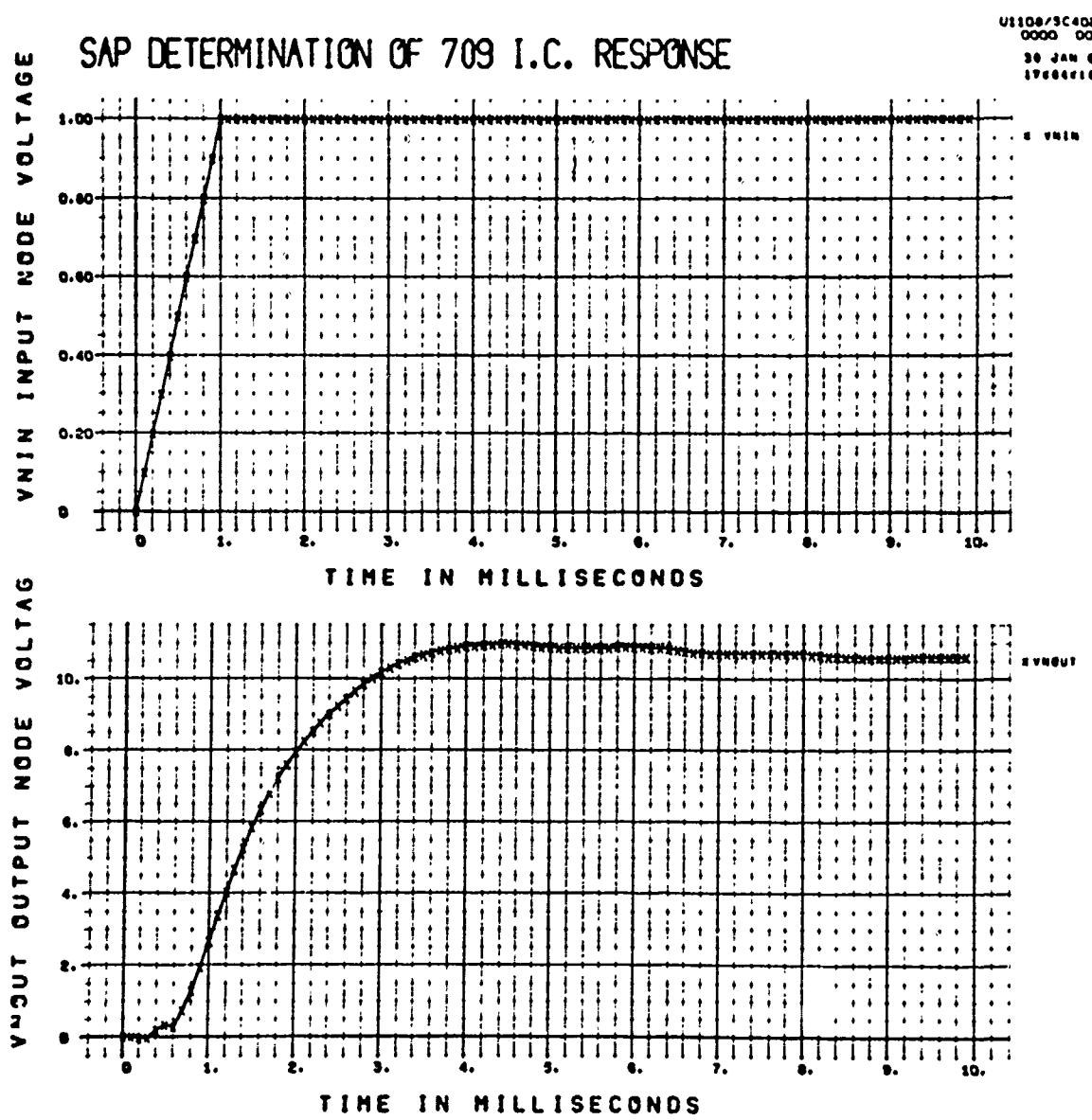
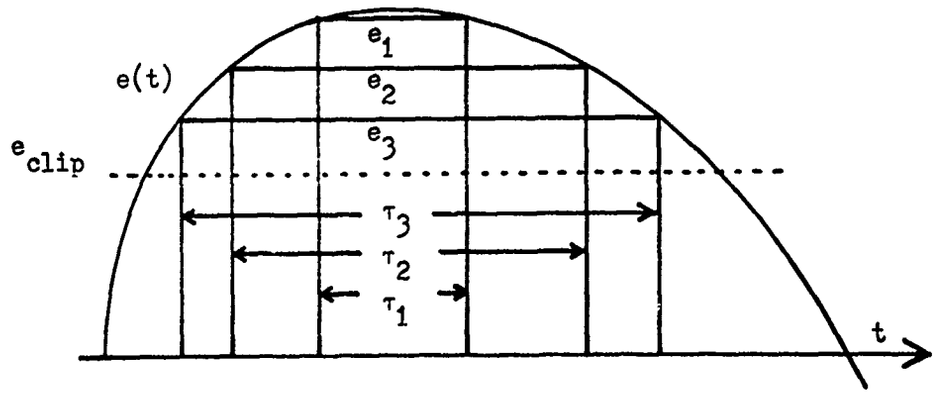


Figure 9. Calculation of Response of a 709 Op Amp to Step Pulse Using Bivariable Propagation with a Nonlinear Response Surface

were generated at the various time steps. Knowing these equivalent varying amplitude, varying length pulses, which constitute the input waveform as shown below:



We then are in a position to calculate the total storage time by the following computer procedure:

- decompose input into separate saturating pulses,
- look up storage time for each pulse (this depends on pulse amplitude and length),
- calculate turn off transfer function,
- combine individual responses using

$$e_o(t) = \sum_j \{ e_j - e_{j+1} \} T_{off}(\tau_s, e_j, t-t_j) \qquad (35)$$

time step increments; storage time; time since pulse turn off

The reasoning behind eq.(35) is somewhat different than simple superposition by virtue of the presence of the e_{j+1} term in the multiplier of the transfer function. The easiest way to understand the term $e_j - e_{j+1}$ is to regard it as a linear interpolation of the effect of different pulse heights. For example, if e_{j+1} is small, say about zero, then we want the maximum charge storage term to be brought in from the saturating pulse e_j; whereas, if $e_{j+1} \approx e_j$, we need only a small contribution from that pulse.

To see how successful or otherwise this approach is, compare the results shown in Figure 10 calculated using eq.(34) alone with those in Figure 11 which was calculated using both (34) and (35). In other words, Figure 10 used just the turn on transfer function surface while Figure 11 used the storage time surface and the turn off surface in addition.

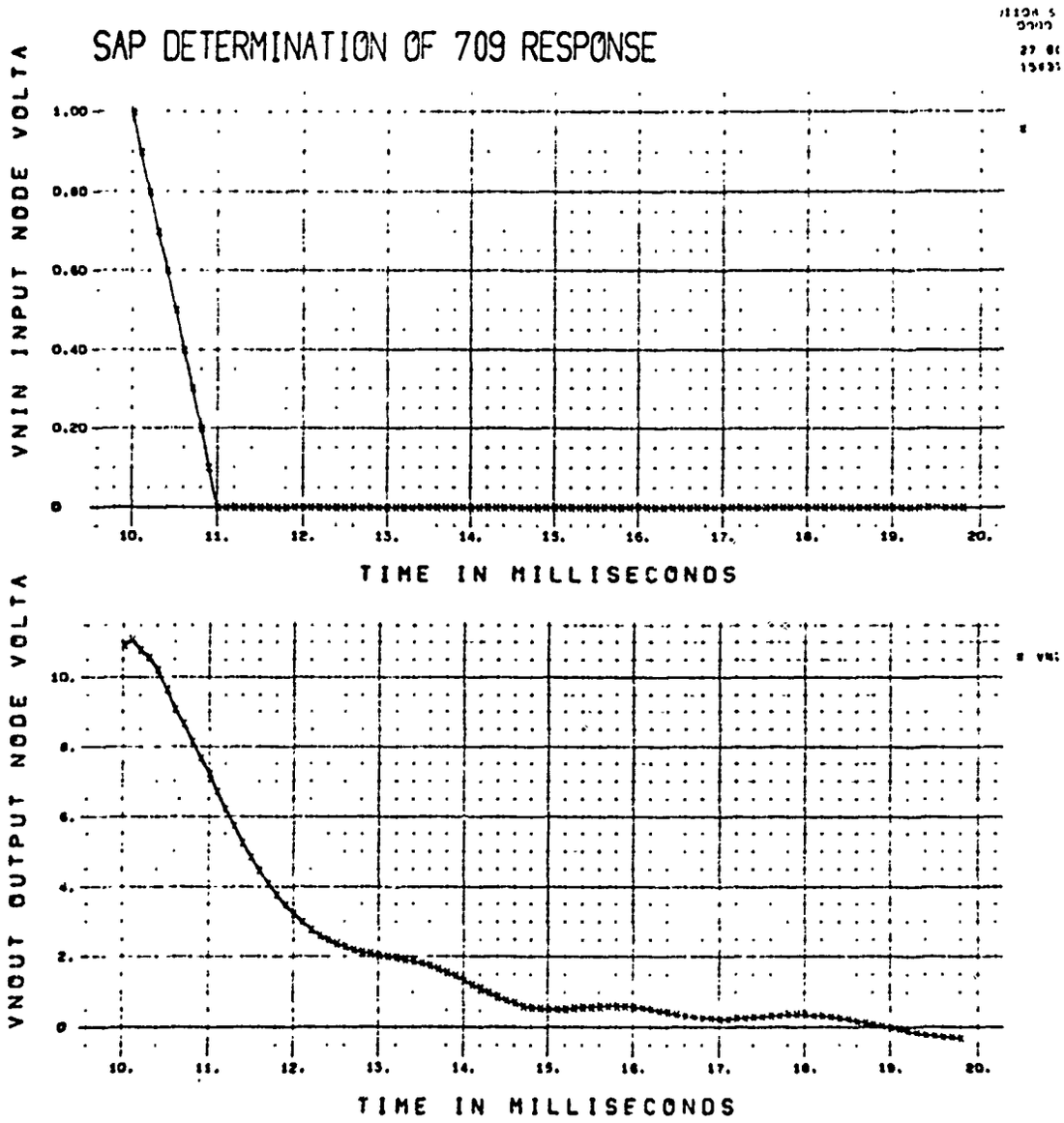


Figure 10. Turn off Portion of 709 Response Calculated Without use of Turn off Surface for Storage Effect

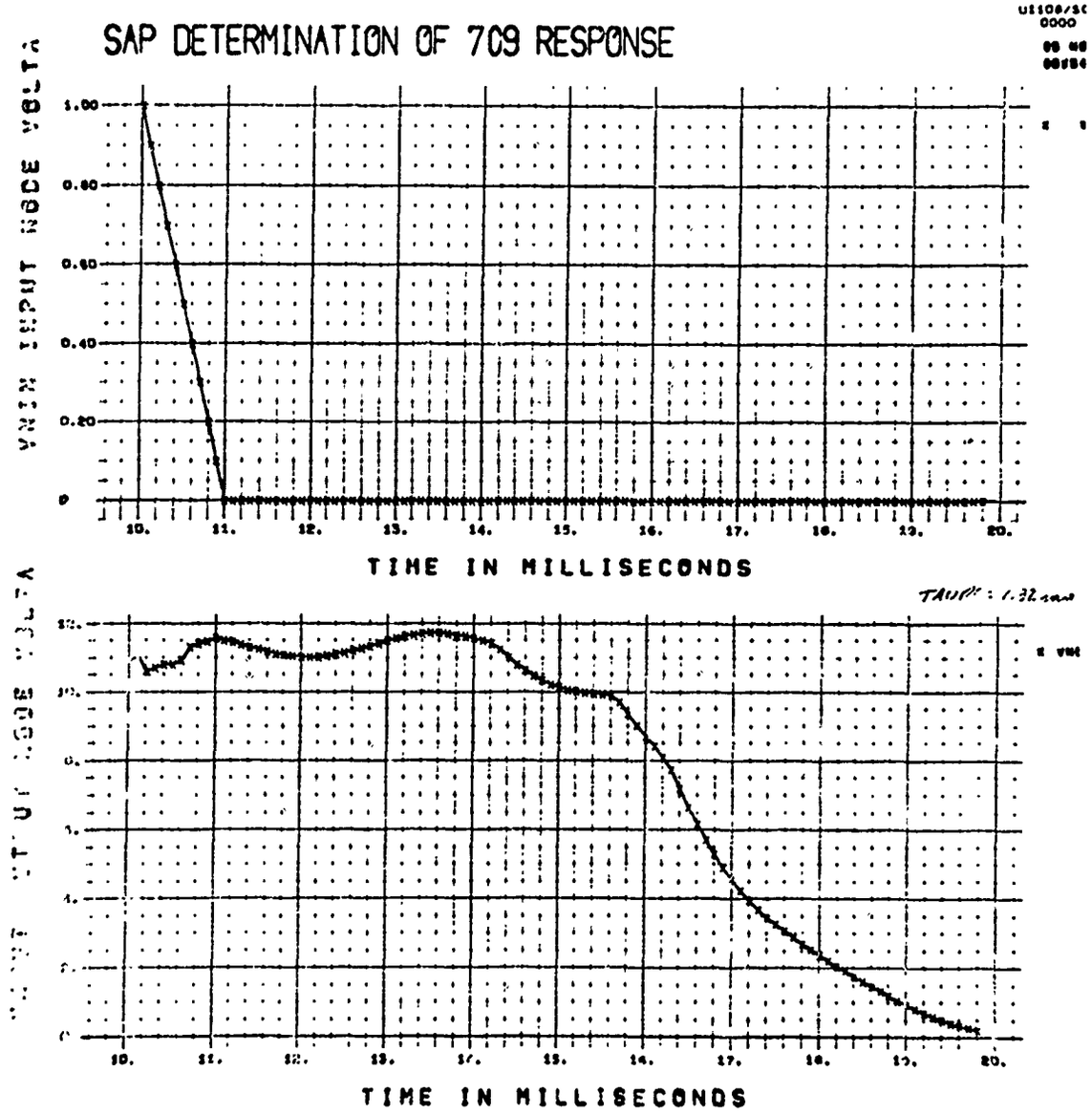


Figure 11. Turn off Portion of 709 Response Calculated Using the Turn Off and Storage Time Surfaces

It is apparent from Figure 11 that the storage effect has been calculated with a modicum of success. The variation of the output in the supposedly constant saturation region is $\pm$ 1 v out of about 10 v. It thus appears possible to use a version of the principle of superposition and obtain results of about 10% accuracy, for charge storage class of nonlinearity.

The results which are shown in Figure 11 used the computer generated fit to the storage time surface that is shown in Figure 7. Figures 10 and 11 show the calculated turn off of a 1.0 mv pulse whose rise is given in Figure 9.

SECTION III

GATHERING THE EXPERIMENTAL DATA

The experimental information on the radiation sensitivity of the devices was taken during three trips to Kirtland Air Force Base and Sandia Base in Albuquerque, New Mexico, during April and May, 1971.

The fixtures used for the flash X-ray exposures at AFWL consisted of sockets affixed on one side of one-half of a lead brick. A hole was drilled diagonally through the brick large enough for the cable circuit cable drivers and Tektronix CT-2 current transformers which were mounted in a Pomona chassis box on the rear of the brick. Thus, the lead length was approximately $2\frac{1}{2}$ inches to the output coupling circuitry. The second NAND gate in the 9704 structure was used as the load for the gate under test. Thus, the load is simultaneously irradiated in good simulation of a weapon burst.

The non-irradiated electrical measurements on the devices were taken at Stewart Research Enterprises in Los Altos, California using the following measurement equipment ensemble:

Pulse Generators - Data Pulse 101, E-H 131, G.R. 1217-C

Oscilloscopes - Tektronix 531 and 535 with CA and 1S1 (Sampling) plug-ins.

Digital Voltmeter - HP3459A

X-Y Recorder - Moseley Model 2

For the fast pulse measurements on the gate circuits, the X-Y recorder was used to record the DC voltages from the 1S1 sampling plug-in. For the slower pulse measurements on the operational amplifiers, Polaroid pictures were taken of the oscilloscope waveforms.

The conditions used during the 741 operational amplifier measurements at the Kirtland flash Xray (FXR) were:

$V_{cc} = \pm 15.00$ volts

R_i = 820 ohms (on both inverting and non-inverting inputs)

R_f = 50 megohm

R_L = 2 kilohm

During the measurements at the Sandia pulse reactor (SPR) the long cable runs necessitated lowering the feedback resistor in order to achieve stability.

1. OPERATIONAL AMPLIFIER TEST CIRCUITS

a. Sine Wave - Non-Radiation Transfer Characteristic

The electrical input - output transfer characteristics were made using the circuitry given in the block diagram of Figure 12a, and specific connections to the op amp shown in Figure 12b. The test sequence utilized was:

1. Insert op amp in test socket.
2. Adjust offset null potentiomenter for zero volts output.
3. Increase oscillator output until op amp output displays limiting.
4. Photograph transfer characteristic with Polaroid camera.

b. Op Amp Response

The pulse response of the op amps were made with the block diagram shown in Figure 12c. The test sequence consisted of the following steps:

1. Adjust offset null potentiometer for zero volts at output.
2. Adjust attenuator and pulse generator to provide desired input signal, and
3. Observe and photograph during reactor pulse the waveform of the output signal.

2. DIGITAL LOGIC GATE TEST CIRCUITS

a. Transfer Characteristics - Before and After Reactor Pulse

The transfer characteristics of the gates were obtained using a curve tracer connected as shown in Figure 13a. The measurement steps are:

1. Note that the oscilloscope is referenced to +5 v for this measurement.
2. Display Base voltage (0.5 v/div) vs Collector voltage (0.5 v/div) as a plot of e_o vs e_i.

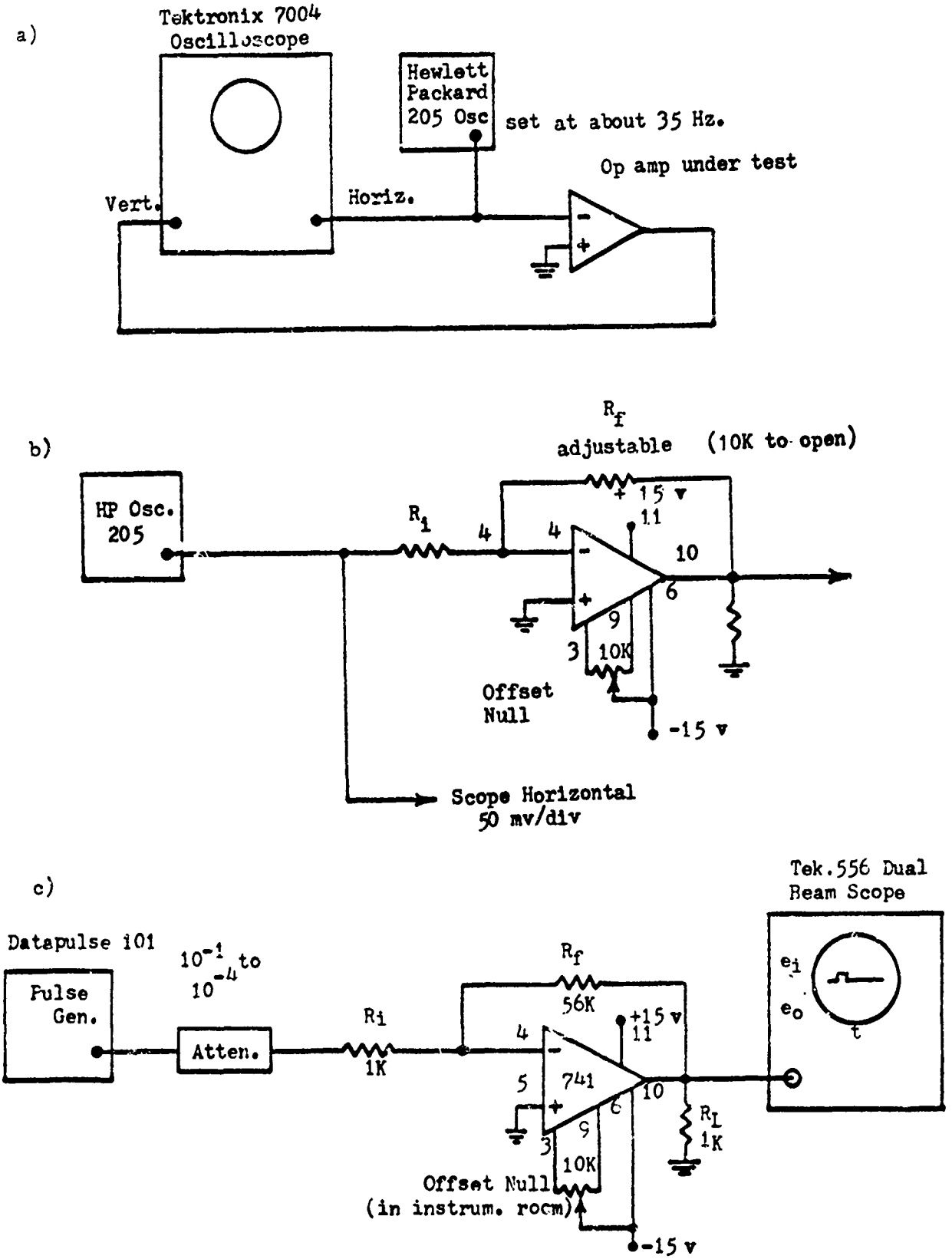


Figure 12. Block and Circuit Diagrams Used for 741 Op Amp Input-Output and Step Pulse Response Determinations

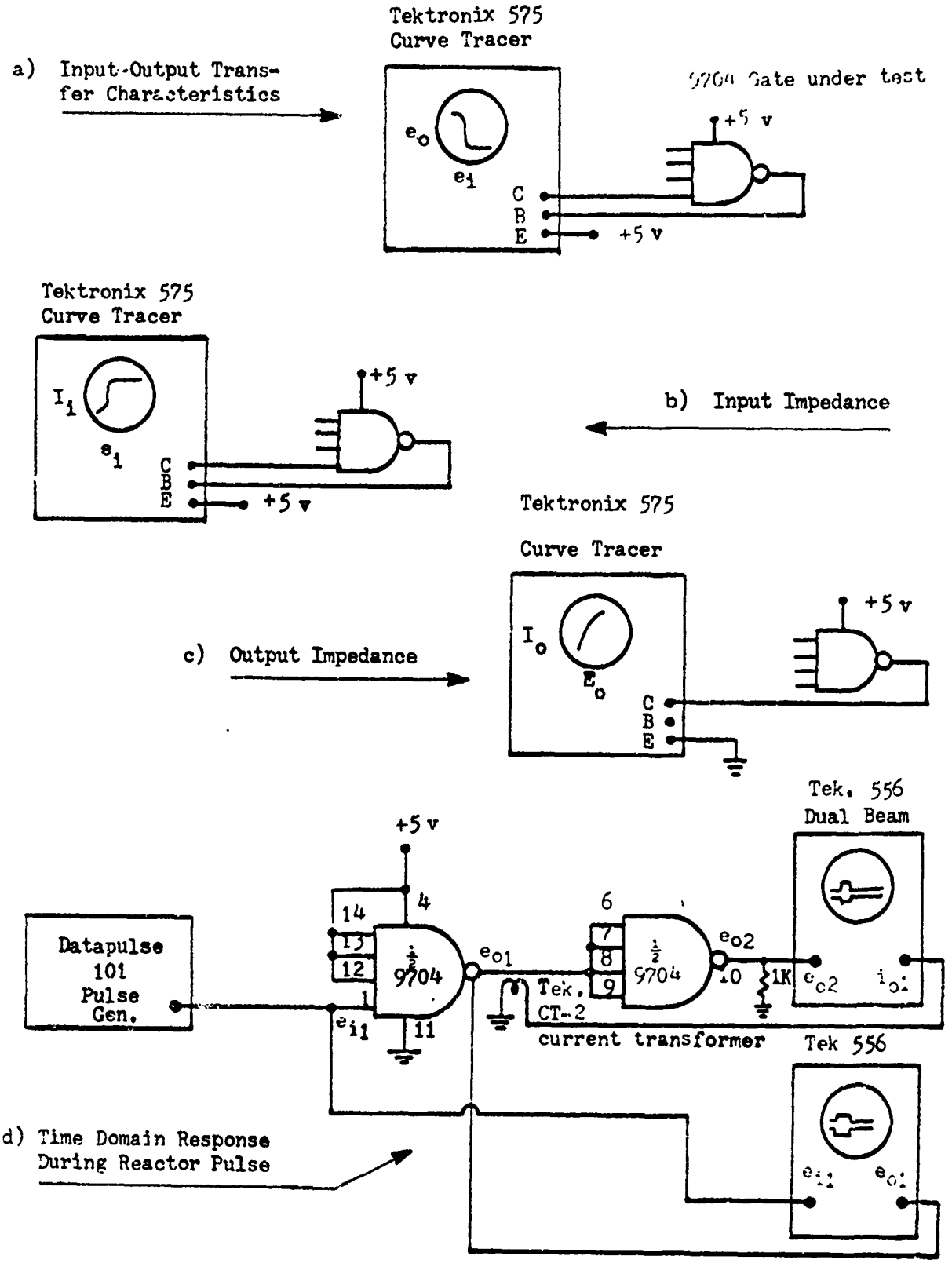


Figure 13. Circuits Used for Measurement of 9704 NAND Gate

3. Set collector sweep at minimum and negative polarity with the dissipation limiting resistor set at 100 ohms,

4. Hold the "zero current" switch in the open or zero current position with a rubber band (this disables the normal base step generator).

5. Increase the collector sweep till e_i sweeps from +5 v to zero, and

6. The transfer characteristics is now observed showing shifts in the gate ON or OFF voltage, and the transition voltage.

b. Input Impedance

The gate input impedance was obtained with the circuit shown in Figure 13b, and the following measurement steps:

1. For this measurement, the oscilloscope is again referenced to +5 v.

2. Change the vertical display to collector ma., (0.2 ma/div)

3. The display is now input current vs. input voltage.

4. Look for excessive leakage current near +5 v input, shifts in transition voltage, and current drawn at zero input voltage.

c. Output Impedance

The impedance test sequence used the connections shown in Figure 13c, and the following measurement steps:

1. The oscilloscope is now referenced at ground instead of + 5 v.

2. Set Collector Sweep at minimum required with positive polarity.

3. Set the zero to the lower left and bottom of the display with the positioning controls.

4. Change the vertical display to 20 ma/div.

5. Increase the Collector Sweep until e_o sweeps from zero to approximately $1\frac{1}{2}$ or 2 v, taking care that the pattern does not change due to device overheating, and

6. Observe the display for change in saturation voltage.

d. Gate Time Domain Response During Reactor Pulse

Circuit configuration used for the gate pulse response during irradiation is given in Figure 13d.

SECTION IV

PROCESSING OF EXPERIMENTAL DATA

The techniques used for processing the raw data into the final function surfaces underwent an evolutionary change during the course of the research. The first method utilized hand made perspective drawings, and was applied to the electrical and radiation response data for the 741 op amp. This technique offers one principal advantage-- the creation of the final surface is an act of decision between noisy data from different test devices, and different experimental situations. Judgement can be used to weigh the significance of a local anomaly as compared to a real trend. As a result the initial surfaces which were evolved looked "good" in the subjective sense. However, the large amount of time required to process the data by this approach makes an alternative mandatory.

Thus, the decision was made to resort to computer processing techniques exclusively for the response surfaces of the 9704 NAND gate. This required extension of the initial machine programs which used least square fitting of three dimensional cubics over each segment of a basic 20 by 20 fitting grid. The cubics are matched in terms of function and derivative value in the spline sense at the grid interstices. The extension required writing a linear interpolation routine to fill in regions of the data space which lacked sufficient experimental data. Then other routines were adapted that performed wild pointing and/or smoothing on the data set. The number of smoothing passes varied in the processing. The effect it has on the result will be shown later.

While machine processing is certainly much easier and faster when the routines that do the real work are written and available, judgement and choice really can not be forgotten. Just how much smoothing is "right" in a certain sense is an esthetic question, rather than a technical one. Let us now see why as we look at different methods and their results.

1. RESPONSE FUNCTION SURFACES OF THE 741

Figure 3 shows the voltage transfer function surface of the 741 with respect to step pulse inputs. This surface is much better behaved than the similar surface for the 709 which was presented as Figure 2 earlier in this report. Yet there are obvious similarities between the two. This drawing shows the faster response of

the device as it is driven hard into the non-linear range by the boundary between the hyperbolic sheet and the rising front portion moving to earlier and earlier times at high signal amplitude. This surface was taken with the device mounted in the fixture made for testing at the Kirtland FXR. The conditions of the measurements are:

$V_{cc} = \pm 15.00$
$R_i = 820$ ohms (on both inverting and non-inverting inputs)

$R_f = 50$ megohm
$R_L = 2$ kilohm

The waveforms were photographed on a Tektronix 535 oscilloscope. The pulses were supplied by a General Radio 1217-C pulser driven at about 5 Hz pulse repetition frequency. Of significant interest to this modeling activity is the very small storage of the 741 as compared with the 709, at least prior to neutron irradiation. After neutron irradiation, storage is evident as shown in the Figures 86 and 87 of Appendix , where the top-hat or butterfly effect of the irradiated 741s is discussed. We will use a three-dimensional computer fit of splined cubics to the T_e surface.

Figure 14 is the radiation transfer function of the 741 as measured using the AFWL Febetron. This surface is more of an impulse response surface, as compared to step response of Figure 3. The vertical axis, labeled T_φ, is the ratio of the output voltage to the $\log_{10}\varphi$, where φ is essentially $\dot{\gamma}$, in rad/sec. Logarithmic time and dosage axis are used because of the large ranges in these variables. It is evident that the 741 is a fast device indeed in terms of radiation effects; whereas, the response to electrical stimulus is relatively slow. The radiation effects are seen on 50 ns time scales, whereas the T_e surface shows phenomena on millisecond or tens of millisecond time scales. This is significant in assessing the effects of inverse feedback on the radiation reponse. From the form of the two surfaces, we expect inverse feedback to hardly reduce the fast nanosecond transient at all, but to significantly reduce the long time hang-up of the device due to radiation.

It is evident by inspection of Figure 14 that the radiation response does not scale simply with dosage. At low dosages, say less than 3×10^8, the response increases until the positive peak is saturated at the supply voltage. It takes another

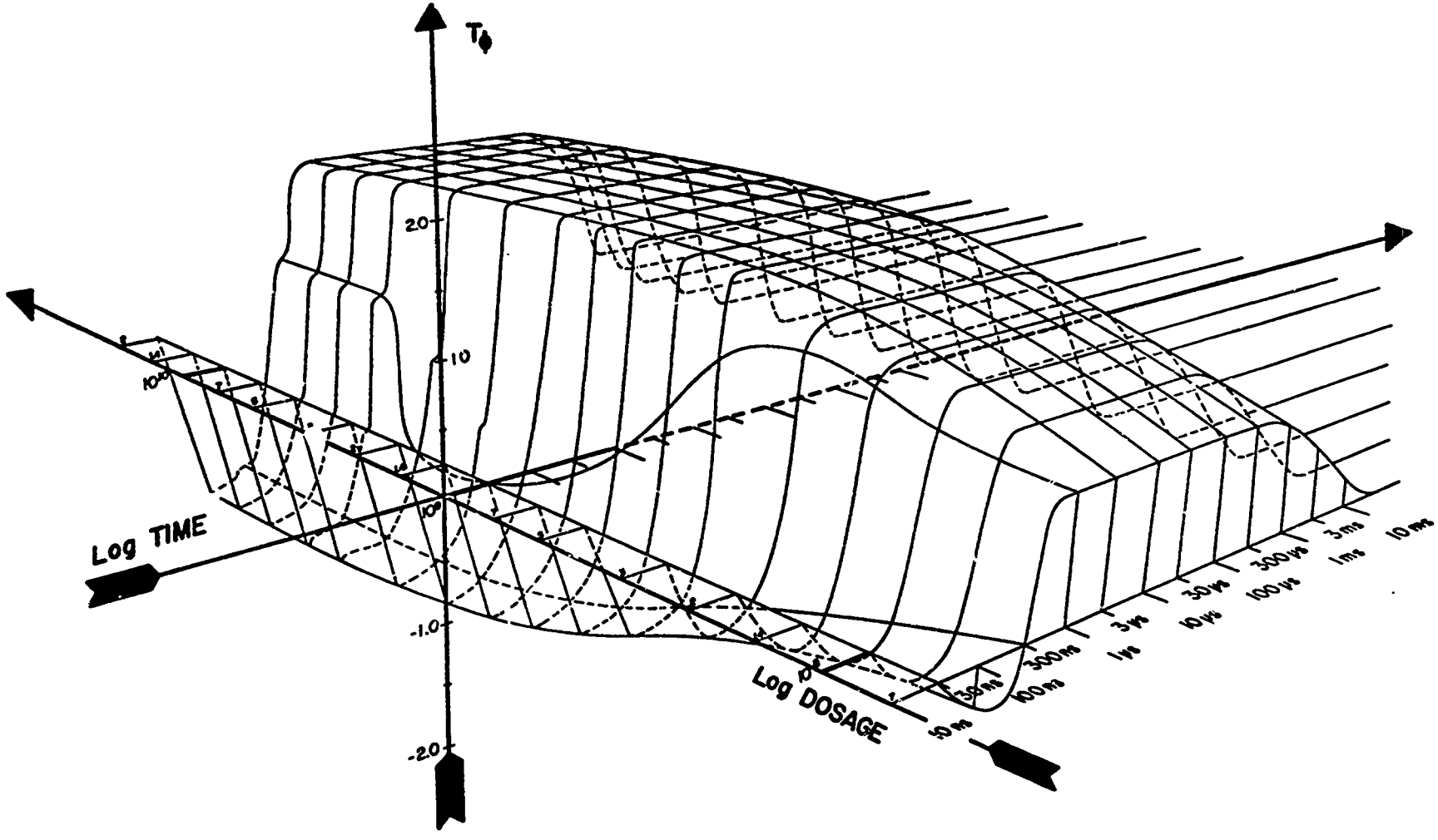


Figure 14. Voltage Transfer Function of the 741 Op Amp due to FXR Irradiation

order of magnitude of radiation to saturate the negative peak. Also interesting is the way the surface recedes on the rising cliff part at intermediate dosages. This shows up most clearly in the drawing by the way the 1 μs isochronal (constant time line) plunges downward. The pulse hang-up time also increases at large dosages. Observe this by noticing how the far back top edge angles backward with respect to the 300μs and 1 ms and 3 ms isochronals. A small flat porch-like structure is evident on the rising cliff at high dosage. This may be due to structure in the FXR pulse, although that would seem unlikely so far in time along the response surface.

The final response function surface for the 741 is based on data taken in May 1971 at the Sandia pulse reactor in Albuquerque. In order to show the phenomena occurring at high dosage, three separate sections have been drawn. Again log time and log dosage axis have been used. The vertical axis, T_φ, is the same as for Figure 14. The dosage is integrated neutron flux with energy more than 10 kev. The pulse length of the reactor is about 50 - 100 ms, and a typical pulse is shown in Figure 85 of Appendix I. A phenomenon evident in Figure 15 is the dramatic destruction of the device at high dosages, as evidenced by the fall off in T_φ above 10^{13}. Thus, we see that this type of representation of a devices radiation transient response at the same time tells us something about the permanent degradation.

Figure 15a shows the front portion of the high dosage transient response. Note that at high dosage the device responds faster, as shown by the isochronals climbing upward on the front cliff. Above about 1.4×10^{12} nvt, a valley occurs after the rising cliff part of the waveform. This valley increases in depth, reaches a minimum, and then starts coming up again, both with respect to time and dosage.

Figure 15b shows the dropping part of the transient waveform toward the minimum of the valley. Note the porch like structure evident at about 150 μs. At high dosage, degradation is also clearly evident on the minimum of the valley.

Figure 15c shows the rising positive portion of the transient response after the valley, and how this is effected at high dosage by the device destruction or degradation. Above about 5×10^{12}, the pulse hang-up time increases greatly (remember this is a log time scale), extending out to about 40 ms. The extent of

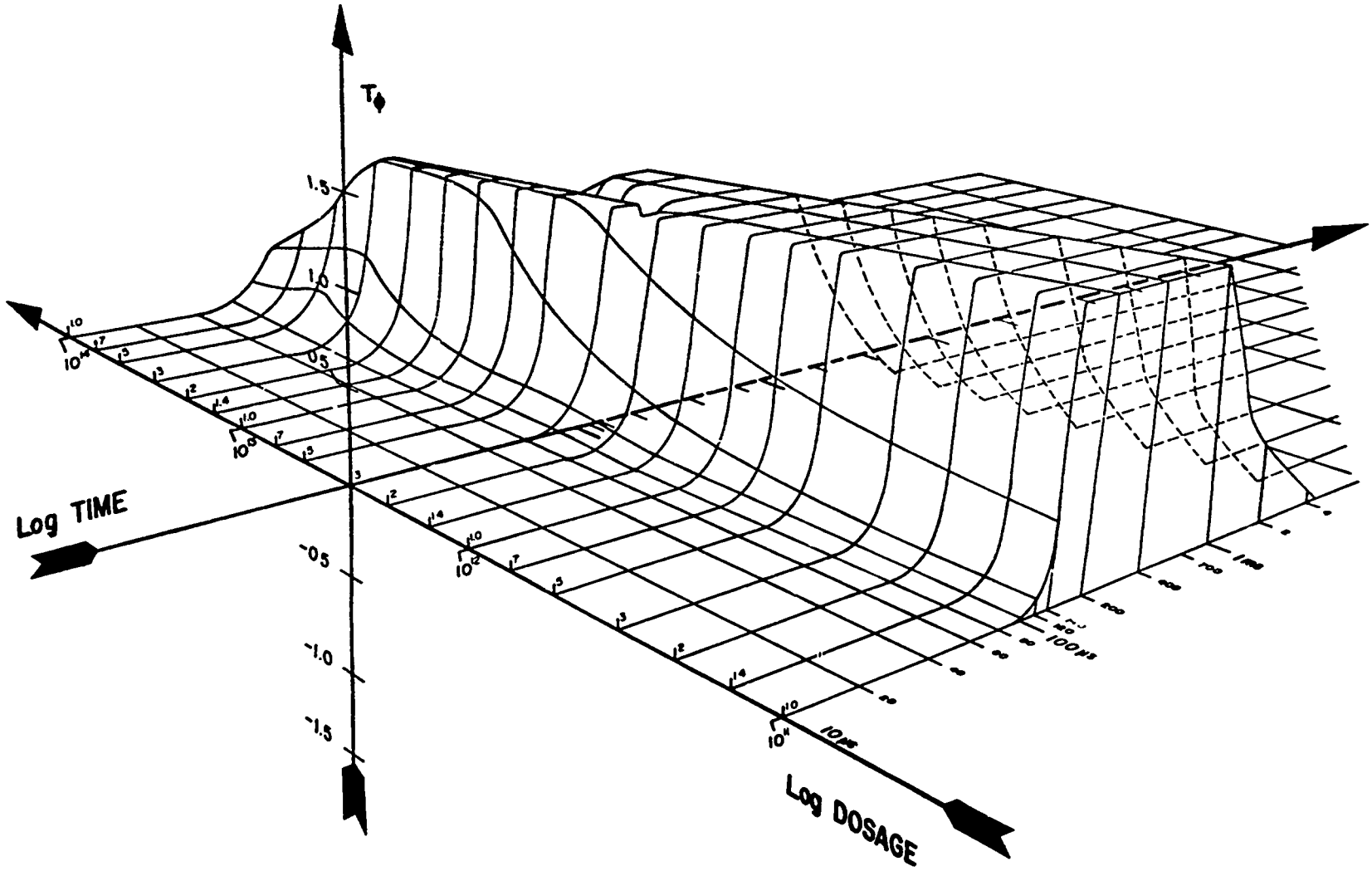


Figure 15a. Radiation Transfer Function Surface for the 741 Operational Amplifier as Obtained with the Sandia Pulse Reactor. Note Degradation at High Dosage.

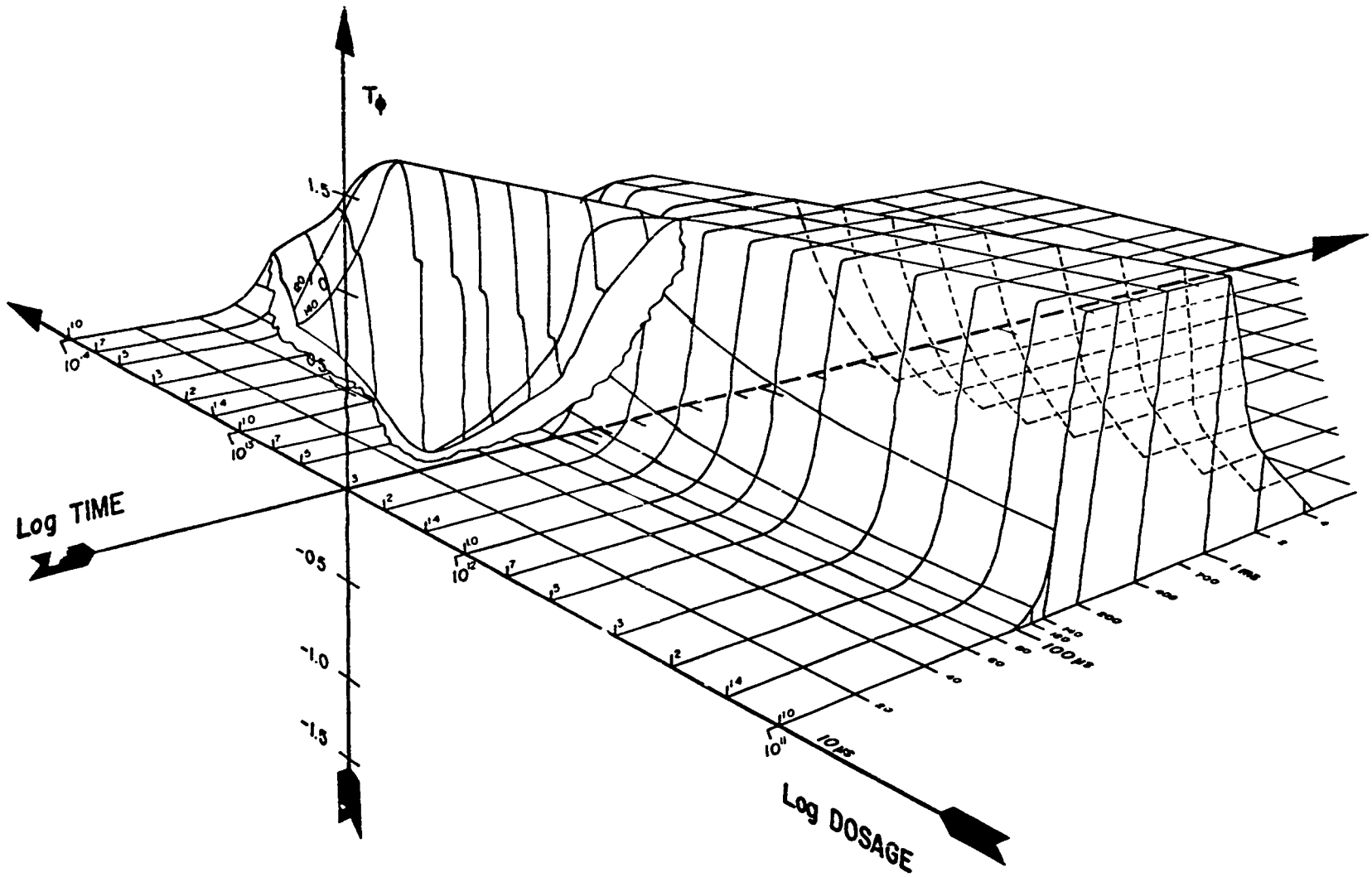


Figure 15b. Radiation Transfer Function Surface of the 741 Op Amp Taken at the SPR with the Front Surface Cutaway Showing Surface Dropping Toward a Valley. Note Degradation at High Dosage.

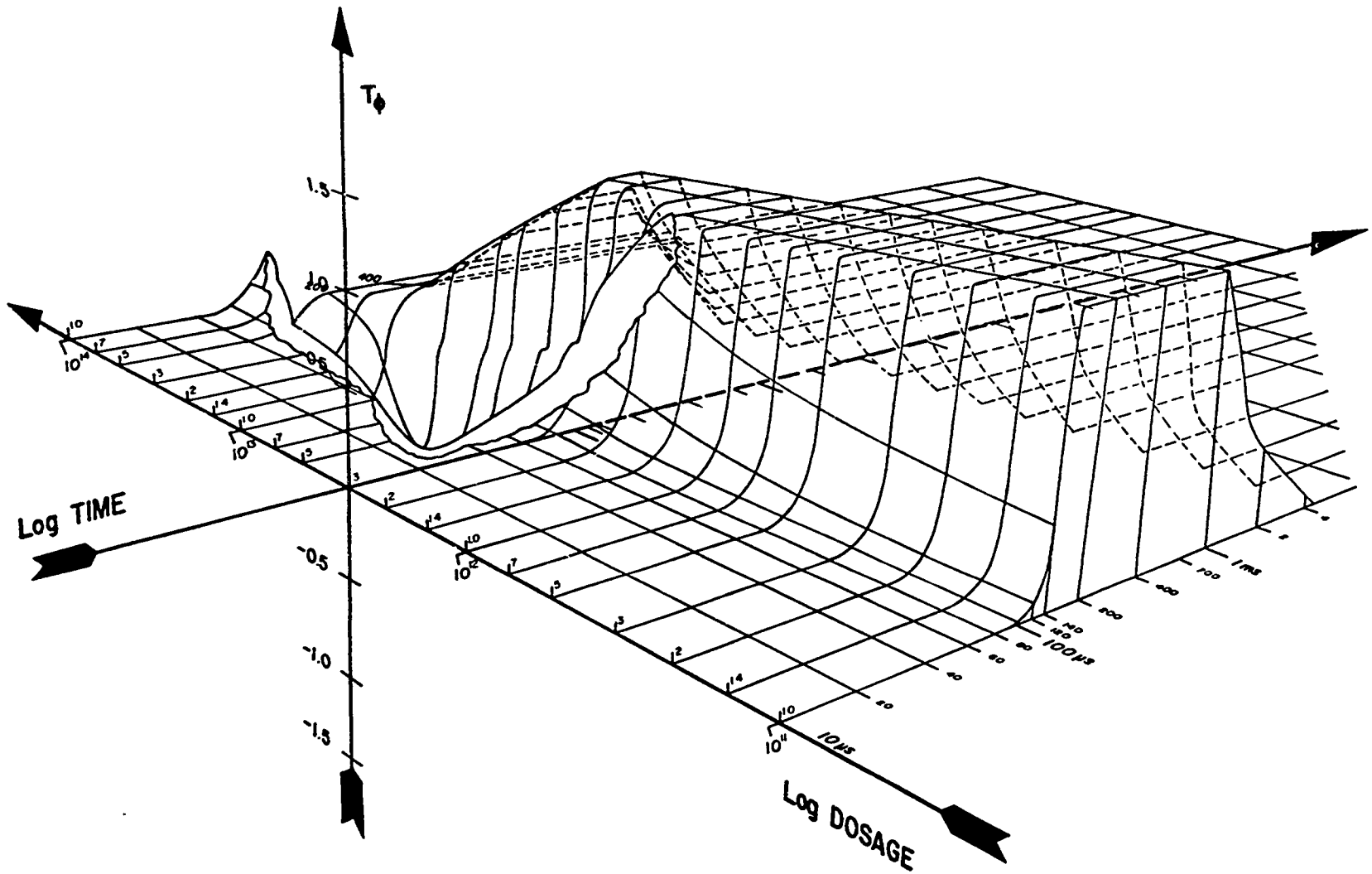


Figure 15c. Radiation Transfer Function Surface of the 741 Op Amp Taken at the SPR with the Front Ridge Cutaway Showing the Rise from the Valley to the Final Ridge. Note Degradation at High Dosage There Also.

this increase in the pulse hang-up time will be more evident in the later computer plots where the perspective view is rotated so that rear portion is visible.

2. HOW THE SURFACE DRAWINGS WERE MADE

The drawings of Figure 15 were not made by a computer. They were drawn using three point perspective grids at four times normal size. The actual dimensions of the original artwork of the drawing is 3 feet high by 4 feet wide. This permits reasonable accuracy to be obtained in plotting the experimental data. Normally five straight-edges are required to translate a point from the coordinate plane to a point in space on the drawing. The data from the original pictures usually does not correspond to nice even values of time or dosage. Hence, the isochronals and isodose lines are created by interpolation between the actual experimental results. To a certain extent this act of interpolating is an exercise in judgement. This is beneficial since nuances of individual devices can be weighed one upon another. However, in actuality there was much more commonality than difference amongst them. Probably the most variable aspect was the offset drift of the op amps in time. For the sake of these drawings, random offset drift was zeroed out.

While considerable effort was required to draw these response surfaces by hand, it is conceivable to couple an on-line computer to the instrumentation during the data acquisition phase at the FXR and the SPR, and create these surfaces automatically using standard three-dimensional surface fitting and projection routines. With the basic data stored, different projection angles can be chosen to optimize the perspective seen. We did not have that advantage for example in drawing Figure 15, where only after most of it had been drawn did we realize that the dosage axis reversed would show the valley behind the first cliff more readily.

The basic data for computer fitting the surfaces for the 741 were obtained from the hand drawings by means of three-dimensional perspective parallelograms. These are used to carry the positional data inherent in some point on the surface back to intersection points along the three fundamental perspective axes. This process is just as time consuming as the original data plot operation was initially. Also it is difficult to avoid errors in the positioning and sequencing of the straight-edges. About 200 data points are the minimum required to represent a surface if symmetry is present and two to three times that if the surface is complex with no symmetry.

3. COMPUTER PROGRAM FIT3D

The basic strategy used to fit and plot the raw data is to establish a two-dimensional grid in the x-y plane of the data set. Normally we will adopt the following labeling convention for the axis, and take them as a right-handed coordinate set:

- x-axis - time or log(time),
- y-axis - input stimulus variable, such as voltage or log(dosage).
- z-axis - transfer or response function.

The dimensionality of the fitting grid is taken as NX by NY, where in all cases that were treated, NX = NY = 20. The dimensionality of the plotting, NGX by NGY, grid was increased to the range of 40 to 50 along each axis in order to achieve reasonably valid plots since the plotted line segments are straight line segments. The fitting grid itself can be coarser since the fitting functions are three-dimensional cubics. The question of how large or small the fitting grid really must be is determined by the degree of deviation which is acceptable between the experimental data, and the machine generated fit. This will be pointed out later in comparing the computer fits to the hand-drawn surfaces.

The computer program FIT3D is a collection of 41 subroutines that create the three-dimensional fitting functions and then plot the resultant surface as an orthographic projection. This file of programs was continually improved and extended during the course of the research program. The main program is FITIT, and the sequence of functions which it calls out are shown in the flowchart of Figure 16.

Three card decks can be punched out by FITIT if desired. These are called ZDATA, ZCOEF, and ZCALC and represent

- ZDATA is a re-ordered version of the inputted data
- ZCOEF is a set of NX x NY cards containing the triplet of numbers $(z, \frac{\partial z}{\partial x}, \frac{\partial z}{\partial y})$ at each interstice of the fitting grid.
- ZCALC is a set of (NGX x NGY / 5) cards with z for each interstice of the plotting grid.

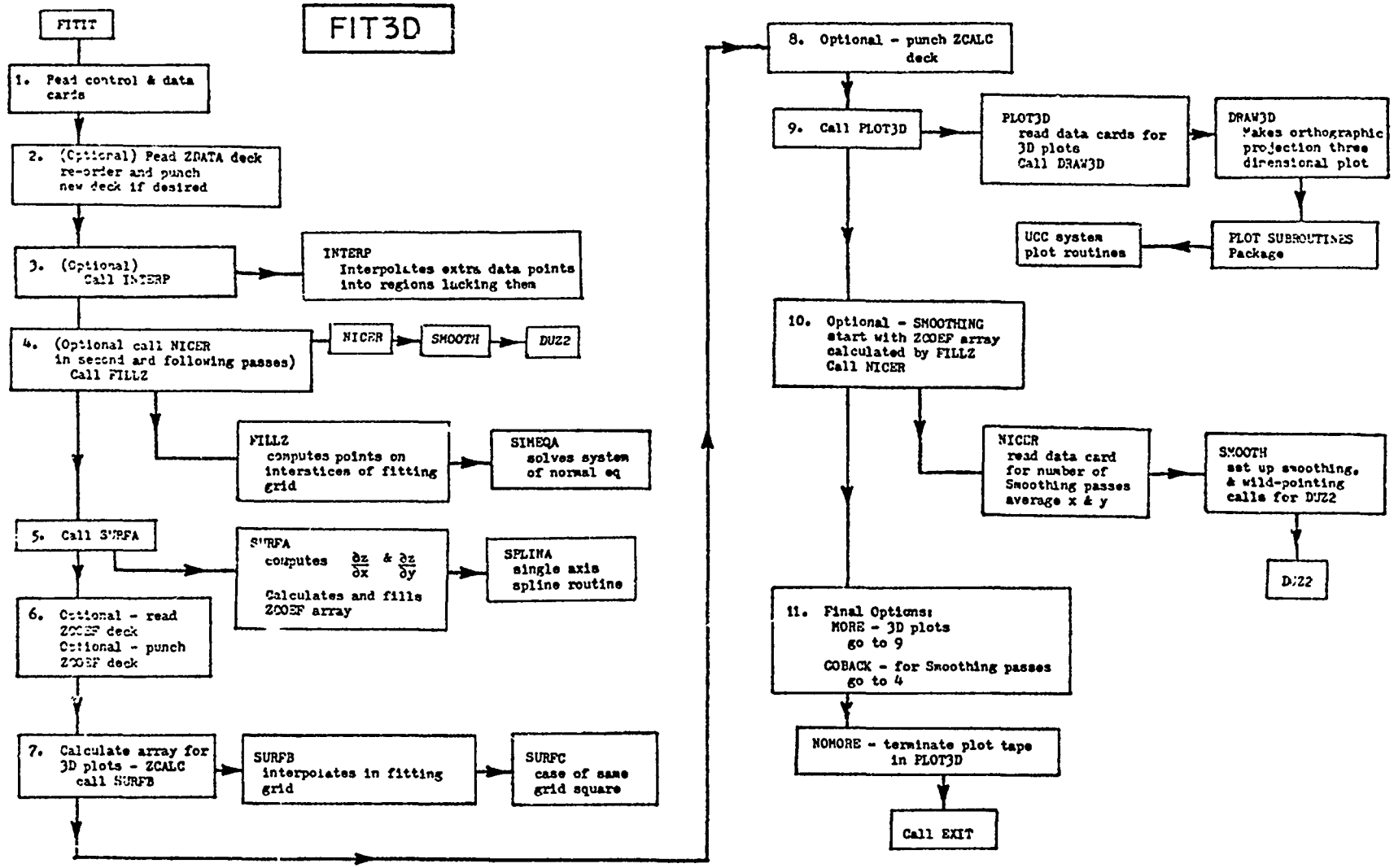


Figure 16. FIT3D Flowchart

The ZCOEF deck or the ZCALC deck may be used to create plots subsequently without the necessity of running through the entire fitting process again. The ZCOEF deck is used in the subsequent program SAP and is hence more versatile, and since it is smaller than the ZCALC deck perhaps preferable for plotting. In some cases it does require driving through the interpolation routine SURFB again, but this only requires five seconds of machine time, which is not excessive.

The logic path taken in FITIT, and the control of the punch operations on the above decks, is determined by the data cards first read in by FITIT. Since the basic input data to FITIT can be brought in from the ZCOEF deck or the ZCALC deck, choice of which one is read is determined by the fourth data card. This card also controls the calling of FILLZ, which performs the creation of least square adjusted data points on the interstices of the fitting grid, or the calling of NICER which sets up the smoothing operations, or the calling of INTERP which can insert additional data points into regions which are deficient in terms of actual experimental data by using linear interpolation between valid data points.

A listing of the initial card reading statements of FITIT is contained in Figure 17. A typical data card deck makeup is presented in Figure 18.

The interpolation of values of z given (x,y) coordinates of a plot point is performed by the routines SURFB and SURFC using the information contained in the ZCOEF array created by SURFA. SURFB locates the input plot point within the proper one of the 400 grid rectangles, and performs interpolation in the three-dimensional cubics using the procedure of Ferguson*. If the plot point happens to lie in the same grid cell as the point of the prior call, the Ferguson coefficients are not recomputed, rather SURFB drops through calling SURFC which uses the Ferguson coefficients of the last pass. These interpolation routines are reasonably fast, performing approximately 500 interpolations per second of Univac 1108 CPU time.

Initially the three-dimensional plots were made using a University Computing Company routine PROJECT. The routine had some operational features which were not satisfactory (such as only plotting positive z values), and did not label and scale the axes of the figure. So, instead the routine DRAW3D was adapted to be compatible

---

J. Ferguson, J.A.C.M. 11, #2, April 1964, p. 221-228.

```
C     GRID DECK ZCALC, FOR PLOTTING BY PLOT3D AND DRAW3D,
C
C*****************************************************************
C
C
      NFIT = 1
      ISERUS=.TRUE.
      WRITE(IT,1001) STAR,FIT,STAR,FIT,STAR,FIT,STAR,FIT,STAR,FIT,STAR,
     1FIT,STAR
 1001 FORMAT(1H1,///,10X, 6(A4,5X,A5,5X),A4  //)
      READ(IN,  1) NGX, NGY
    1 FORMAT(2I3)
      WRITE(IT,  2) NGX,NGY
    2 FORMAT(/6X,6H NGX = ,I3, 10X, 6H NGY = , I3 //)
      READ(IN,  3)  XLO,XHI,YLO,YHI
    3 FORMAT(4E10.5)
      WRITE(IT,  4)  XLO, XHI, YLO, YHI
    4 FORMAT(10X,5HXLO =,G12.5,10X,5HXHI =,G12.5,10X,5HYLO =,G12.5,10X,
     15HYHI =,G12.5   //)
C
      XLO = 0.9999998 * XLO
      YLO = 0.9999998 * YLO
      XHI = 1.0000002 * XHI
      YHI = 1.0000002 * YHI
      XDELTA = (XHI - XLO)/(NGX - 1)
      YDELTA = (YHI - YLO)/(NGY - 1)
C
C     READING THE CHOICE OF SURFACE TO BE PLOTTED
      READ(IN,5)  ISYM
    5 FORMAT(A4)
      WRITE(IT,6) ISYM
    6 FORMAT(10X,8H ISYM  = , A4   //)
C
C     READING DATA CARD TO CONTROL READING OF ZDATA, ZCOEF, AND ZCALC
C     DECKS, AND THE CALLING OF THE INTERPOLATION AND SMOOTHING ROUTINES
C
      READ(IN,7) KFILLZ,KNICER,KINTER,KPLOT3,KZDATA,KZCOEF,KZCALC
      WRITE(IT,1007) KFILLZ,KNICER,KINTER,KPLOT3,KZDATA,KZCOEF,KZCALC
    7 FORMAT(8(A6,4X))
 1007 FORMAT(10X,8(A6,4X)//)
      IF(KFILLZ.EQ.IFILLZ) LFILLZ = .TRUE.
      IF(KNICER.EQ.INICER) LNICER = .TRUE.
      IF(KINTER.EQ.IINTER) LINTER = .TRUE.
      IF(KPLOT3.EQ.IPLOT3) LPLOT3 = .TRUE.
      IF(KZDATA.EQ.IZDATA) LRDATA = .TRUE.
      IF(KZCOEF.EQ.IZCOEF) LRCOEF = .TRUE.
      IF(KZCALC.EQ.IZCALC) LRCALC = .TRUE.
C
C     READING DATA CARD TO CONTROL PUNCHING OF ZDATA, ZCOEF, AND ZCALC,
C
      READ (IN,2007) KPDATA,KPCOEF,KPCALC
      WRITE(IT,3007) KPDATA,KPCOEF,KPCALC
 2007 FORMAT(3(A6,4X))
 3007 FORMAT(10X,3(A6,4X)//)
      IF(KPDATA.EQ.IPDATA) LPDATA = .TRUE.
      IF(KPCOEF.EQ.IPCOEF) LPCOEF = .TRUE.
      IF(KPCALC.EQ.IPCALC) LPCALC = .TRUE.
C
      IF(LNICER) LPATH = 1
      READ(IN,1)  NX,NY
      NXY = NX * NY
      WRITE(IT,8) NX, NY, NXY
    8 FORMAT(10X, 4HNX =, I3, 10X, 4HNY =, I3, 10X, 5HNXY = NX * NY
     1 I5   //)
      IF(.NOT.(LRDATA.OR.LINTER)) GO TO 999
      READ (IN,9) DIVIDR
    9 FORMAT(E10.5)
      WRITE (IT,99) DIVIDR
   99 FORMAT( 10X, 9H DIVIDR =, F10.5, //)
  999 IF(.NOT.LPDATA) GO TO 30
      READ(IN,1027) LOG1,LOG2,LOG3
 1027 FORMAT(3(L5,5X))
      WRITE(IT,199) LOG1,LOG2,LOG3
  199 FORMAT(         43H  THE VALUES OF LOG1, LOG2, AND LOG3 ARE   ,3L3)
C
      READ(IN,1) NREAD
      WRITE(IT,45) NREAD
   45 FORMAT(11H    NREAD =,I2)
C
C     READING RAW DATA FROM CARDS
      ISTOP = 0
      DO  22  I = 1, NMAX
   12   IF(ISTOP.EQ.1) GO TO 24
      GO TO (14,16,18),NREAD
   14   READ(IN,10) (DATA(I,L),L=1,3),ISTOP,(XPRIME(I,L),L=1,4)
        WRITE(IT,15)(DATA(I,L),L=1,3),ISTOP,(XPRIME(I,L),L=1,4)
   10 FORMAT(   3F10.5, I1, 9X, 4A6)
   15 FORMAT(5X,3F10.5, I1, 9X, 4A6)
      GO TO 20
   16 READ(IN,17)      ISTOP,(DATA(I,L),L=1,3),(XPRIME(I,L),L=1,4),GOOD
      WRITE(IT,1702)  ISTOP,(DATA(I,L),L=1,3),(XPRIME(I,L),L=1,4),GOOD
   17 FORMAT(    I1,3F10.4,20X,2X,4A2,2X,L2)
 1702 FORMAT(5X,I1,3F10.4,20X,2X,4A2,2X,L2)
      GO TO 20
   18 READ(IN,19)     ISTOP,DATA(I,2),DATA(I,1),DATA(I,3),(XPRIME(I,L)
     1,L=1,4),GOOD
      WRITE(IT,1902) ISTOP,DATA(I,2),DATA(I,1),DATA(I,3),(XPRIME(I,L)
     1,L=1,4),GOOD
   19 FORMAT(    I1,10X,F10.4,10X,2F10.4,2X,4A2,2X,L2)
 1902 FORMAT(5X,I1,10X,F10.4,10X,2F10.4,2X,4A2,2X,L2)
   20   IF((LOG1).AND.DATA(I,1).GT.0.0) DATA(I,1)=ALOG10(DATA(I,1))
        IF((LOG2).AND.DATA(I,2).GT.0.0) DATA(I,2)=ALOG10(DATA(I,2))
        IF((LOG3).AND.DATA(I,3).GT.0.0) DATA(I,3)=ALOG10(DATA(I,3))
        IF(ISTOP.NE.1.AND..NOT.GOOD) GO TO 12
        IF(ISTOP.EQ.1.AND..NOT.GOOD) DATA(I,3) = 0.0
        DATA(I,3) = DATA(I,3) / DIVIDR
        IF(ISTOP) 24,22,24
   22 CONTINUE
   24 IMAX = I
C
C
   30 IF(LINTER) CALL INTERP(DATA,NMAX,XPRIME,DIVIDR,IMAX,
     1 XLO,XHI,YLO,YHI,NX,NY)
C
      IF(.NOT.(LRDATA.OR. LINTER)) GO TO 61
C
C     SEQUENTIAL REORDERING OF DATA,
C
      IMAXM1 = IMAX - 1
      DO  39  I = 1, IMAXM1
```

Figure 17. Listing of FITIT Read Statements

```
Column Number →
1        10        20        30        40        50        60        70        80
:.....:.....:.....:.....:.....:.....:.....:.....:.....:

$ XYT FITIT
 51 51    NGX  NGY
  1.0        8.5     7.83333  10.333       XLO  XHI  YLO  YHI
ODD      ISYM
                                PLOT3D              RZCOEF
NO PUNCH
 20 20    NX  NY
 -.3287712-01 -.2340861-00  .3319865-00 -.5044898-01  .6748608-01  .2943779-00
    198 MORE CARDS AT THIS POINT FROM THE ZCOEF DECK.
 -.5309451-01 -.1425200-00 -.3379903-00 -.1812959-01  .4699074-00 -.1475317-00
  0.8        SIZE
LOG(TIME IN NANOSECONDS)
 LOG(GAMMA DOSAGE)
   TPHIVX
 RADIATION TRANSFER FUNCTION OF THE 741 OP AMP DUE TO FXR EXPOSURE R 577
TRUE      BYPASS
  0  0  0      IXL  IYL  IZL
   55   20     0    0    OFALSE0.0        0.0        0.9        1.1        0.9
MORE
  170  290     0    0    OFALSE0.0        0.0        0.9        1.1        0.9
MORE
  190  250     0    0    OFALSE0.0        0.0        0.9        1.1        0.9
NOMORE

Column Number →
1        10        20        30        40        50        60        70        80
:.....:.....:.....:.....:.....:.....:.....:.....:.....:
```

Figure 18. Data Card Deck for F I T I T and P L O T 3 D Which Contains Total of 220 Cards

with the Calcomp type calls used by the UCC plotter. When completed the results were rather good, in terms of generating good scales and labels for both the three dimensional plots and the plots created by SAP. Additional effort was devoted to incorporating a hidden line removal algorithm in DRAW3D.

The transformation which DRAW3D uses in making the plots is orthographic projection. The scale is constant over the drawing. The transformation equations from the three-dimensional data to the two-dimensional drawing are:

$$\bar{x}(x,y) = x\, S_x \cos\alpha - y\, S_y \cos\beta$$

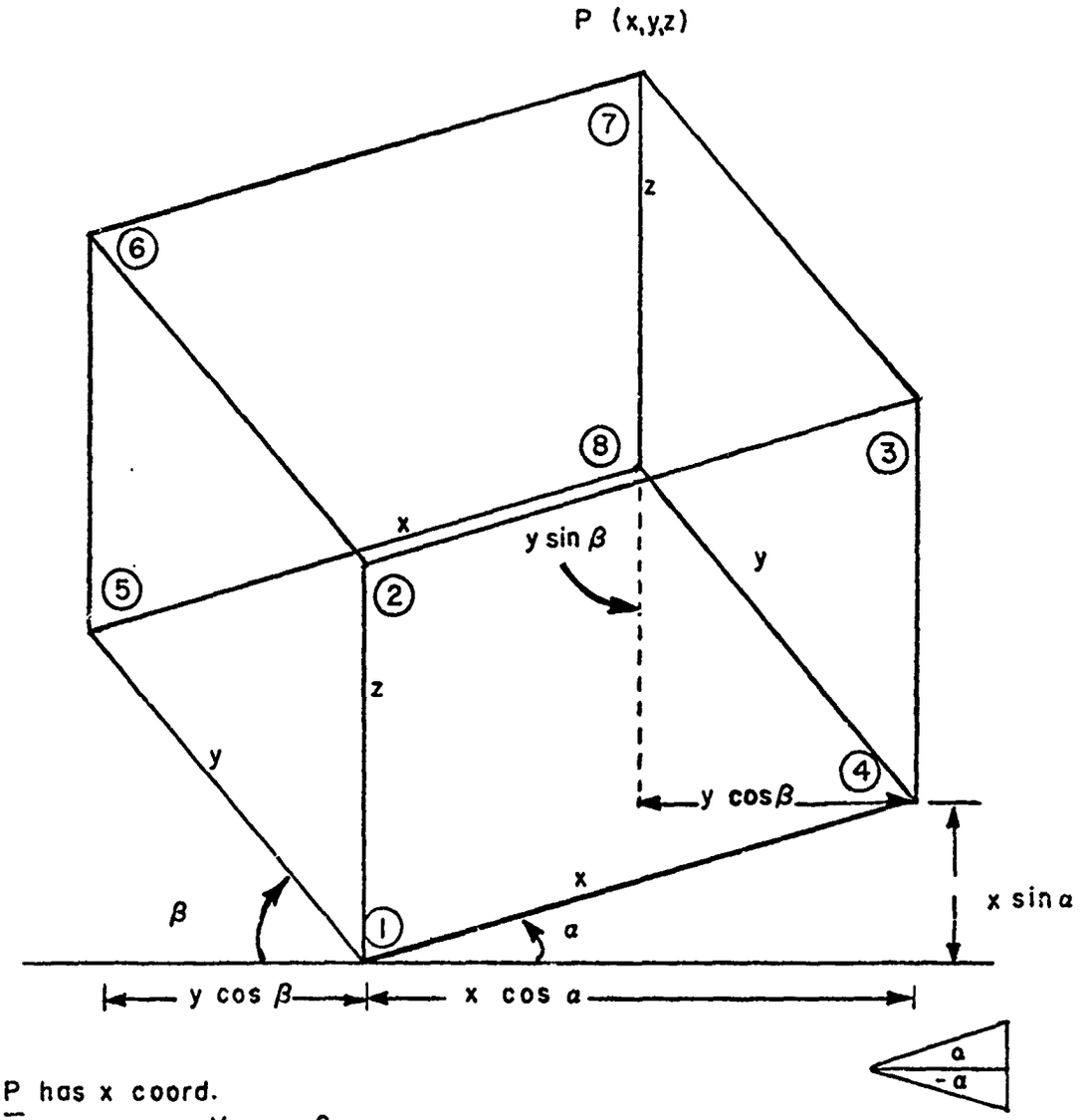
$$\bar{y}(x,y,z) = z\, S_z - x\, S_x \sin\alpha - y\, S_y \sin\beta$$

where S_x, S_y, and S_z are scale factors.

The various views of the surfaces are plotted with values of the angles alpha and beta having the meaning as shown in Figure 19 which is in accord with the previously given definition of the coordinate system and where:

- alpha is the angle measured counter clockwise from the positive horizontal line to the x axis,
- beta is the angle measured clockwise from the negative horizontal line to the y axis.

Predetermining the correct choice of the projection angles α and β was greatly simplified by taking a transparent plastic "picture cube", and marking the x, y, and z axes on it. This was then held up against a 360° protractor of 6 inches diameter in such a manner that the z axis was vertical as viewed; this means the z axis could be tilted to and fro, but not side to side. Then the intersection of the axes along the periphery of the protractor immediately provides the correct choice of alpha and beta to yield the desired perspective. It should be noted that when the z axis is not held vertical during the above operation the resulting plot does not look at all satisfactory, since the orthographic projection of DRAW3D will orient the z axis vertically regardless of α and β.



Point P has x coord.

$\overline{X} = X \cos\alpha - Y \cos\beta$

$\overline{Y} = Z + X \sin\alpha + Y \sin\beta$

$\sin -\alpha = -\sin\alpha$

$\cos -\alpha = \cos\alpha$

Figure 19. Orthographic Projection Utilized for Three-Dimensional Plots of Surfaces

4. COMPUTER FITS TO THE 741 ELECTRICAL AND RADIATION RESPONSE

Because the 741 operational amplifiers surfaces were originally created by hand drawn perspective drawings, the subsequent machine processing was relatively simple compared to the strategies applied later to the digital gate data. In Figure 5 is shown the first fit attempted to the step voltage transfer function surface. This plot was made by the UCC routine PROJECT, with scales and labels added later by LEROY lettering. The hand drawing from which the data were obtained was shown earlier as Figure 3. There are some obvious flaws in the computer fit to the data available to it, namely the "ears" at about $e_i = \pm 0.6$ mv and t = 23 ms. These protuberances result from the relative sparseness of data points in that portion of the surface, combined with the fact that there is a sharp corner in the data itself. The "roundness" of polynomial fitting causes an over and undershoot in such regions. To a certain extent this can be minimized by supplying an abundance of data which tightens up the tolerances allowed by the least square fitting process of FILLZ.

Another area showing deficiencies is in the central front rising section where the first four or five isochronals have an accordion like pleating. Again this is due to a sparseness of raw data, such that the fitting cubics in a given fitting square are not adequately constrained, and so the spline conditions attempt to improve the fit in those areas where the supply of basic data is greater. The second pass at this surface is shown in Figure 20, as plotted by the routine DRAW3D. Note how adding additional data points eliminated the pleating at the initial rise, and reduced to some extent the overshoot or ears on the upper portion. The top portion at the back is also smoother and flatter.

Three views of the gamma radiation response surface of the 741 generated by FIT3D from the original surface drawing of Figure 14, are shown in Figure 21 a, b, and c. It is evident that the overall fitting is rather good. The only place where there is a significant difference occurs on the rising wall at high dosage following the dip to negative saturation. The experimental plot has a shelf which is not reproduced due to the coarseness of the 20 by 20 fitting grid in the machine plots. Two-dimensional cross-sectional plots through maximum and minimum are given for this surface in Figure 22 a and b.

Again note the dramatic difference in the response speed of the device to radiation when compared to electrical stimulus as may be seen by comparing the

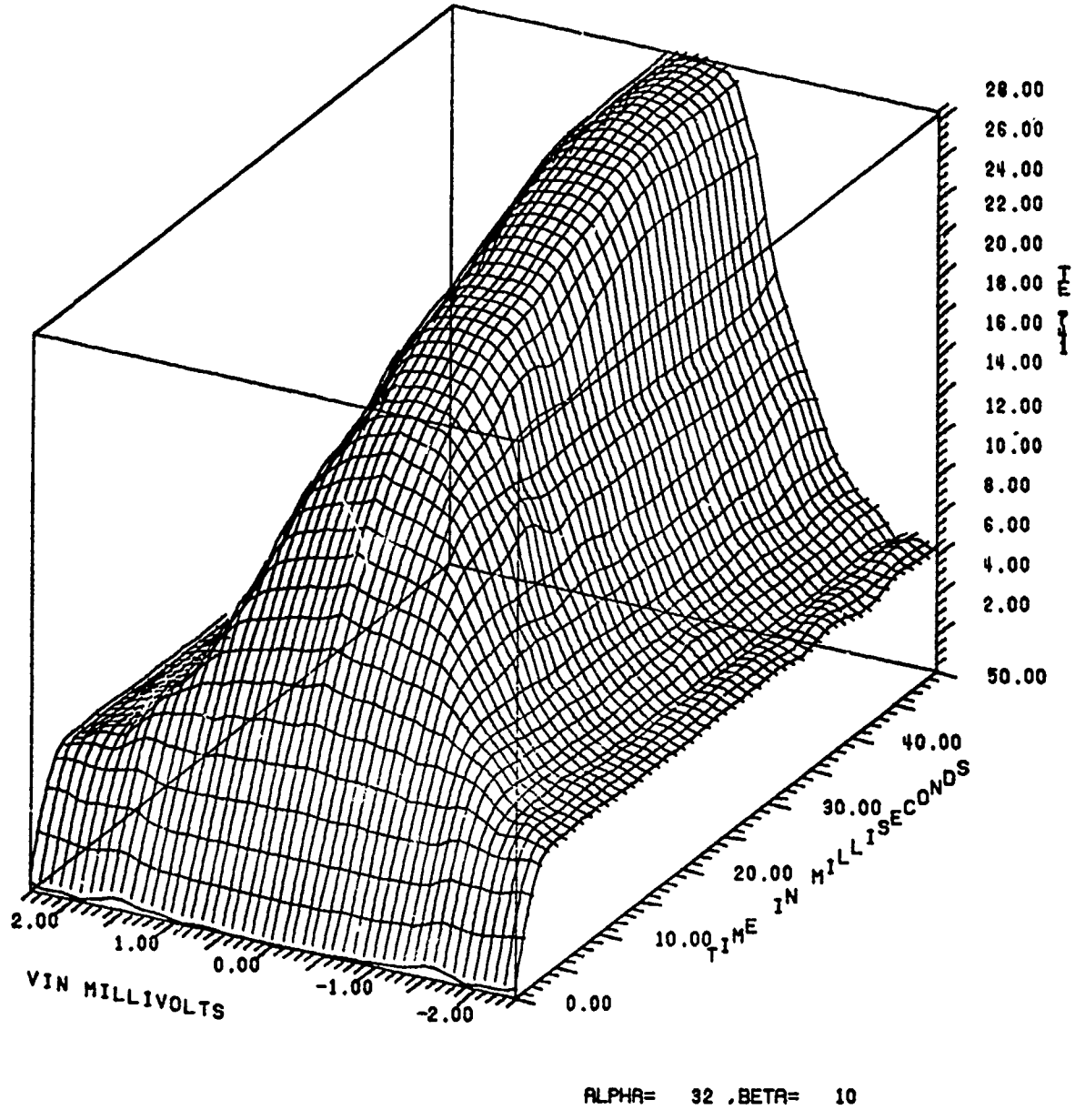


Figure 20. Computer Plot of 741 Voltage Transfer Function

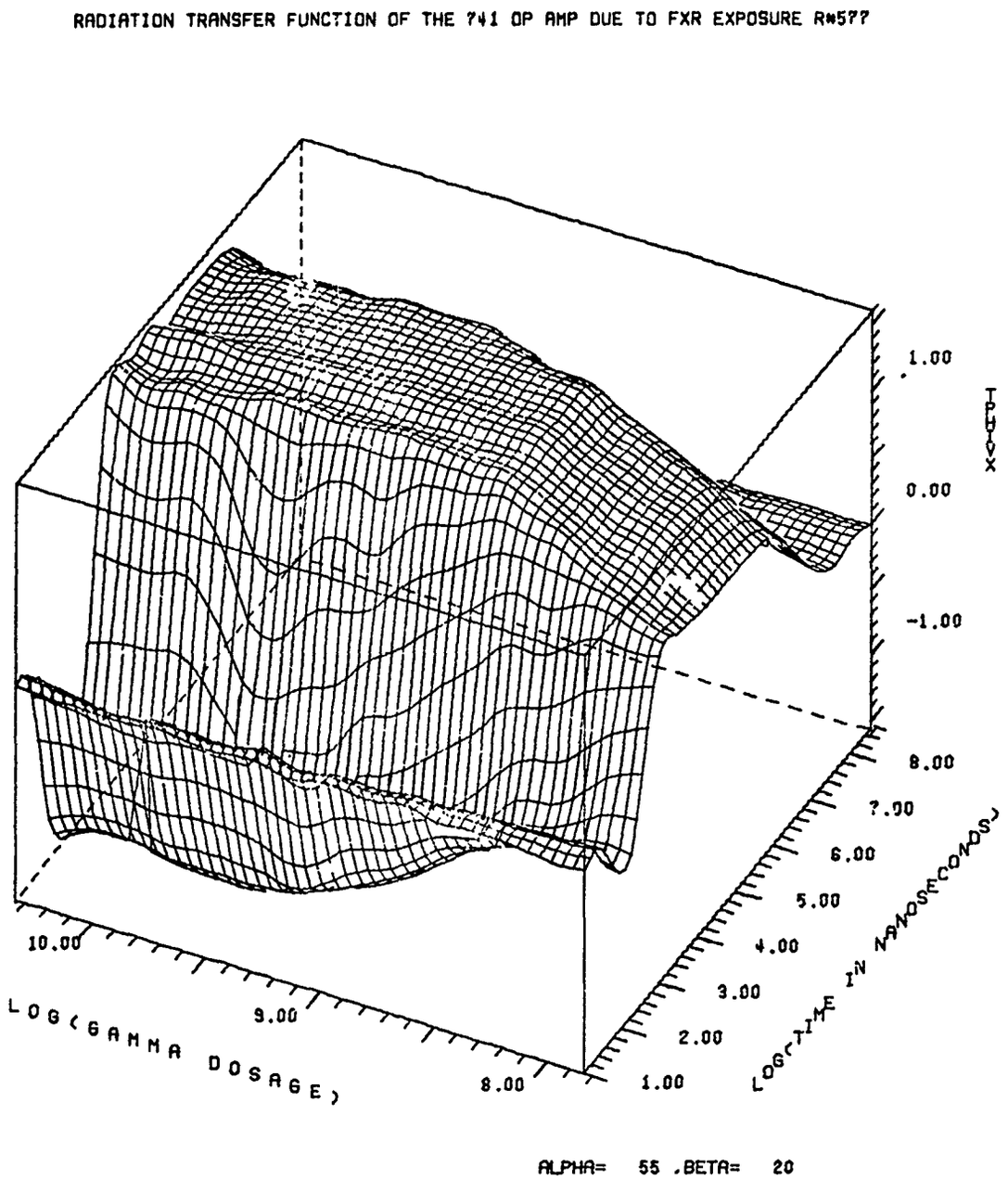


Figure 21. Radiation Transfer Function of 741 due to FXR Exposure

Figure 21a.

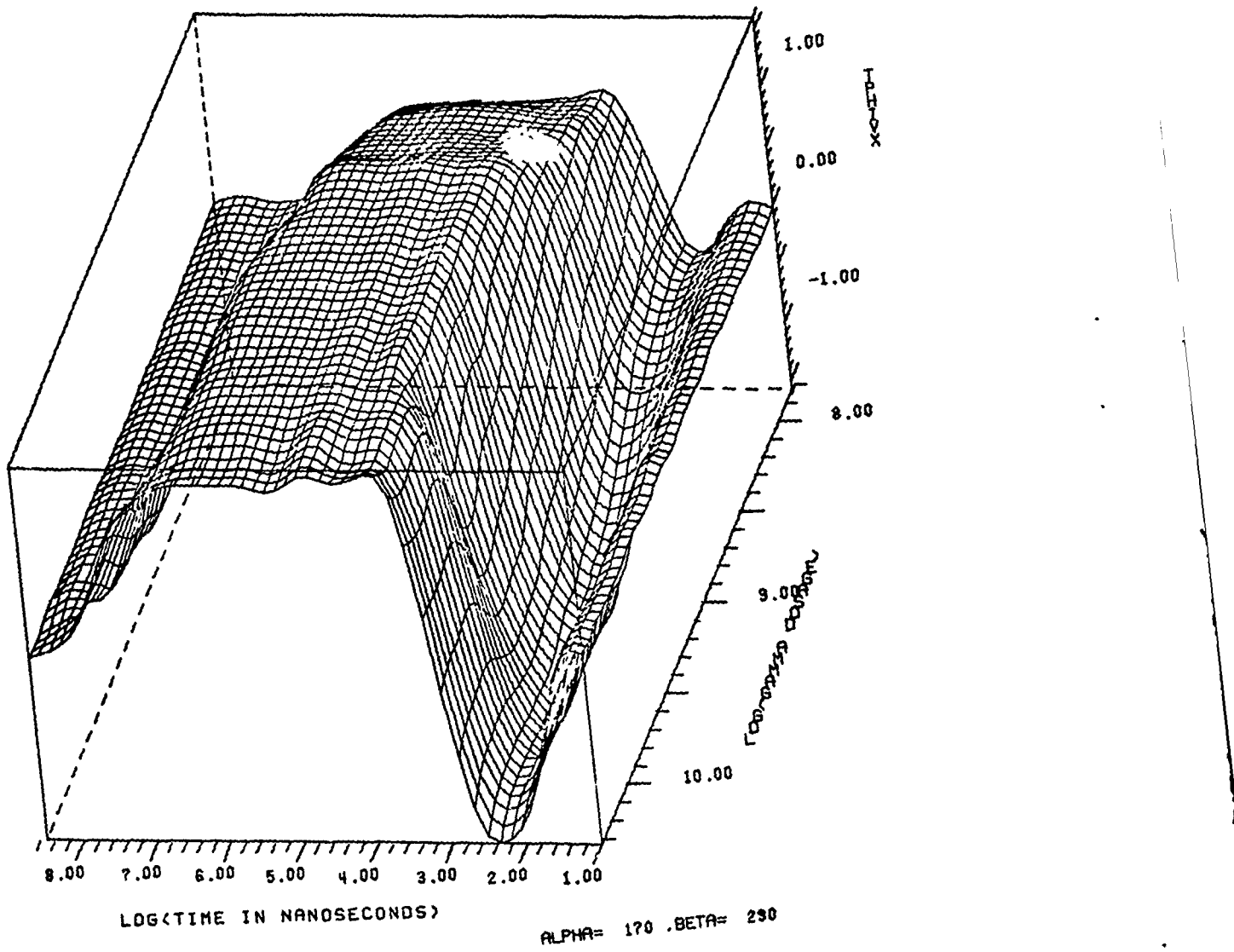

RADIATION TRANSFER FUNCTION OF THE 741 OP AMP DUE TO FXR EXPOSURE R=577
1.00
0.00
-1.00
8.00
9.00
10.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
LOG(TIME IN NANOSECONDS)
ALPHA= 170 .BETA= 230

Figure 21b.

RADIATION TRANSFER FUNCTION OF THE 741 OP AMP DUE TO FXR EXPOSURE R#577

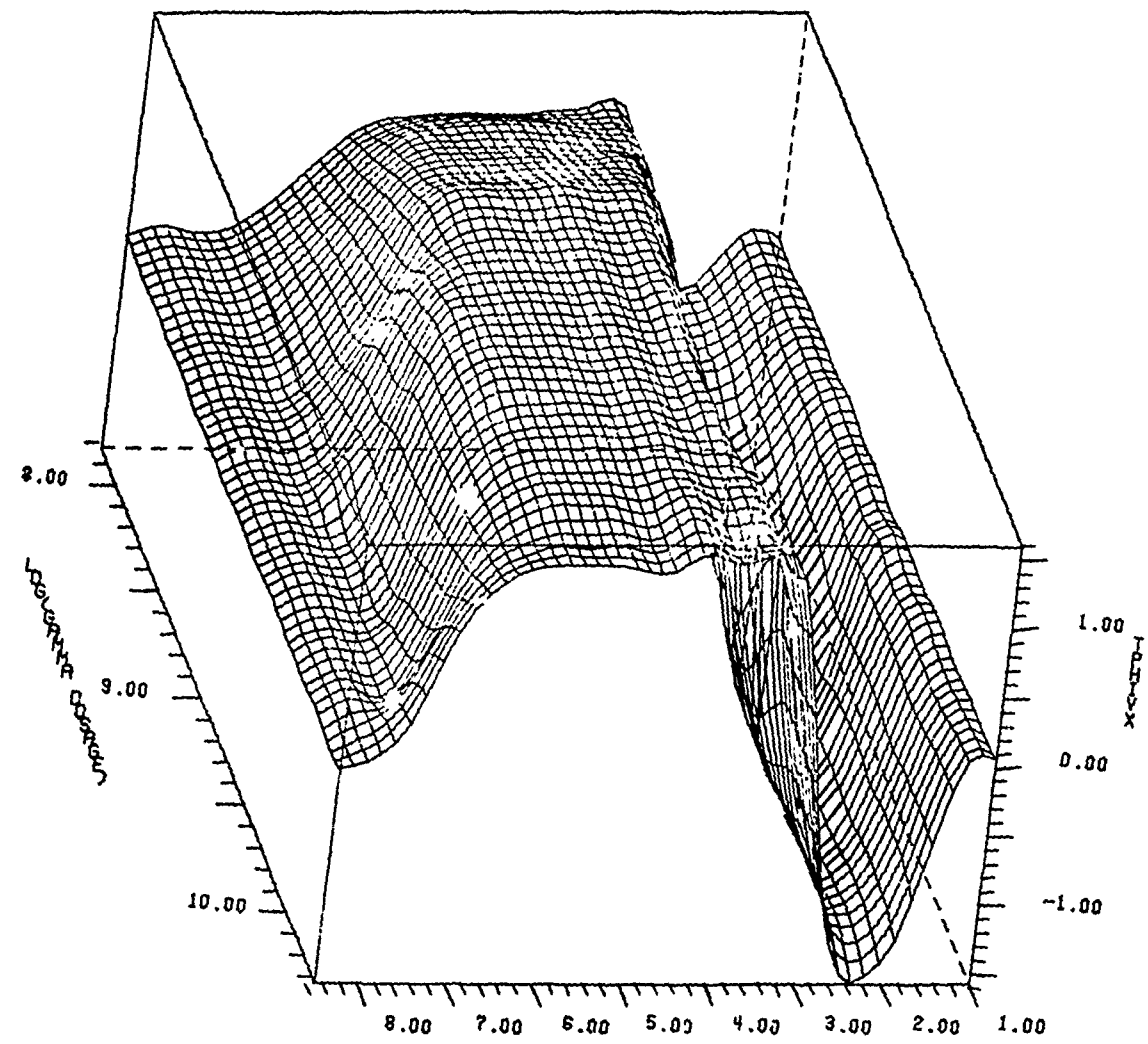


Figure 21c.

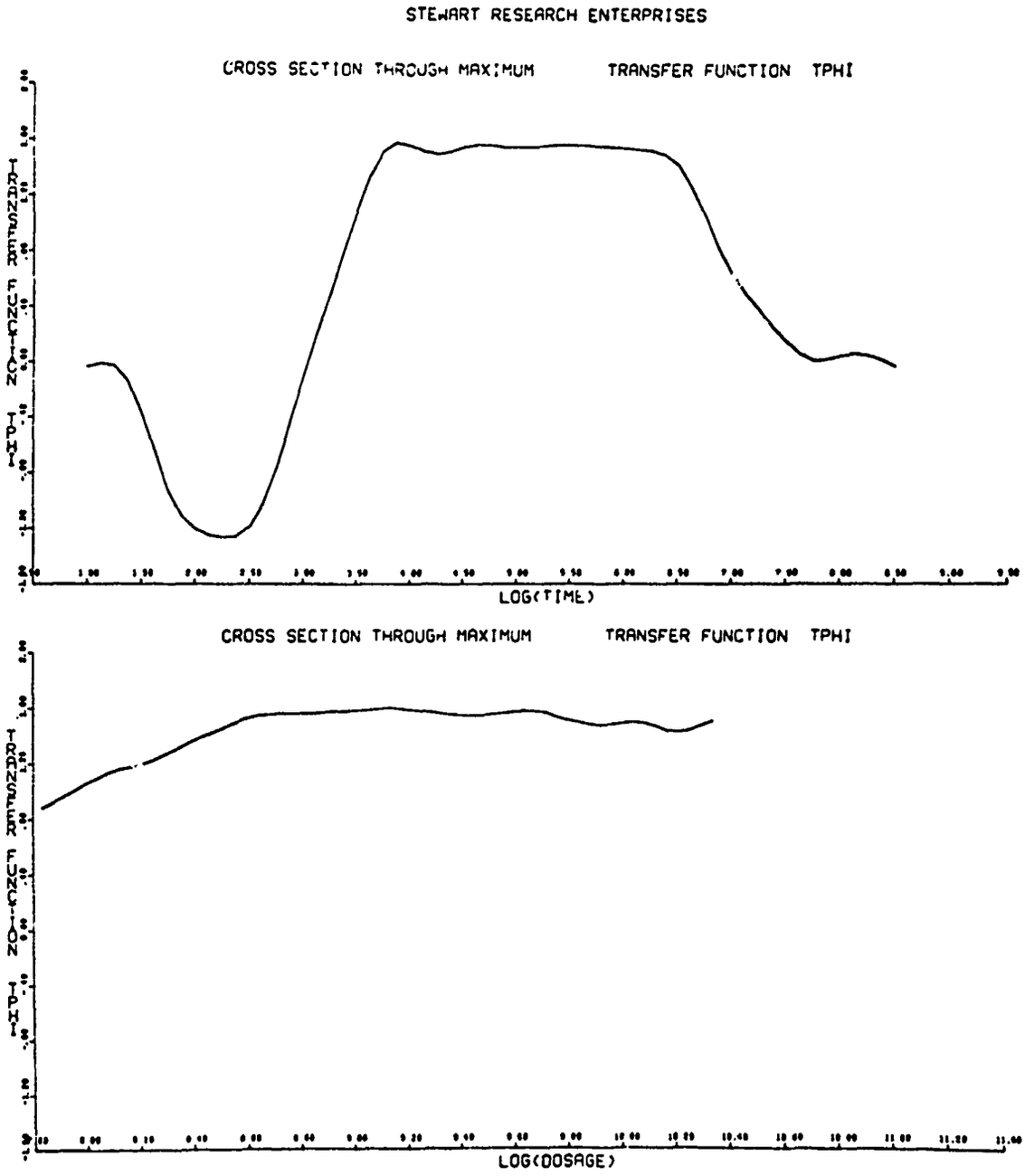


Figure 22a. Cross Section Through Maximum Transfer Function Value of the 741 FXR Surface of Figure 21

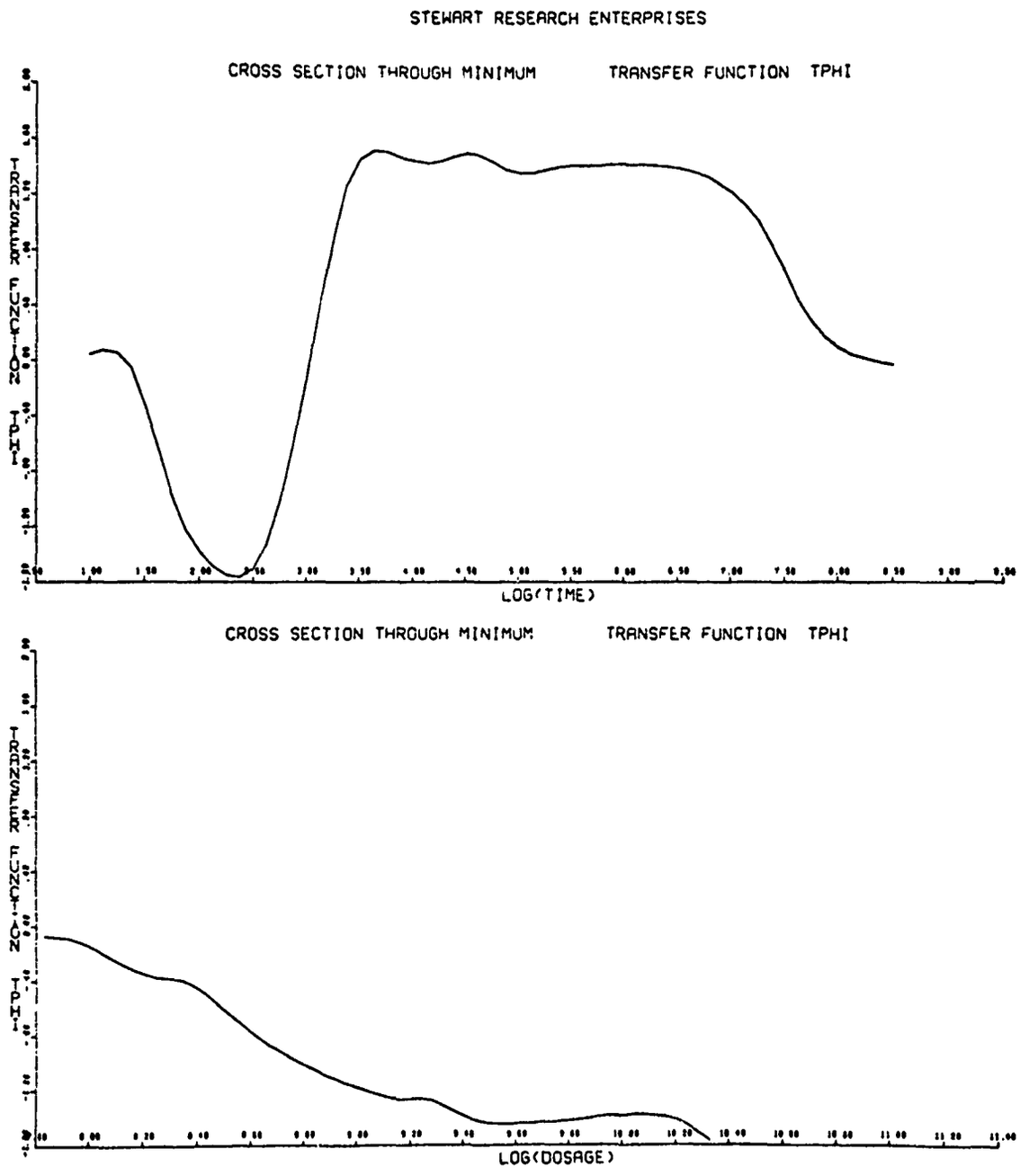


Figure 22b. Cross Section Through Minimum Transfer Function Value of the 741 FXR Surface of Figure 21

time axes of the vacuum cleaner surface, Figure 20, with that of the FXR surface, Figure 21.

The computer representation of the neutron response function surface of the 741 as obtained with the Sandia Pulse Reactor (SPR) is shown in different projection views in Figure 23 a, b, and c. Here we note the great advantage of the computer in being able to rotate the view angle so that we can peer right down the valley, which was so laboriously treated by successive overlays in Figure 15. Two-dimensional cross-sectional views for this neutron surface are given in Figure 24 a and b.

Of particular significance to this work is the cross-sectional plot on the bottom of Figure 24 b, where TPHI versus log (dosage). This curve essentially shows the destruction of the device at very high dose. It seems to represent permanent degradation, in addition to the basic transient phenomenon; few devices survive close shots at the SPR. Thus by defining an appropriate isochronal at a time of approximately 700 microseconds, the permanent damage to a device for a given accumulated dose would appear to be calculable from the same surface that depicts the transient response. This should not be expected to be true in all cases. The way this damage isochronal is used in the circuit analysis code SAP will be discussed later.

The neutron surface shows again the general validity obtainable with the 20 by 20-fitting grid. The results are good in the "big" sense. Note that the fit is not quite a faithful representation because of the absence of a shelf on the rising and falling portions of the valley, as may be seen by comparing Figure 5 with Figure 23.

A last aspect of the radiation transfer function surfaces for the 741 op amp which is of fundamental significance is the logarithmic scale for both the dosage and time axes. This is not only of great significance in terms of the machine fitting process itself, but also will be of high value later in the system analysis operations in SAP in considerably reducing the time constant and execution time problem for certain classes of simulation. However, a logarithmic time axis does not prove acceptable for some of the digital gate response surfaces. That is, the complexity of the response must reduce with time in order for a logarithmic time base to be acceptable. The 741 surfaces show that this does happen for some integrated circuits.

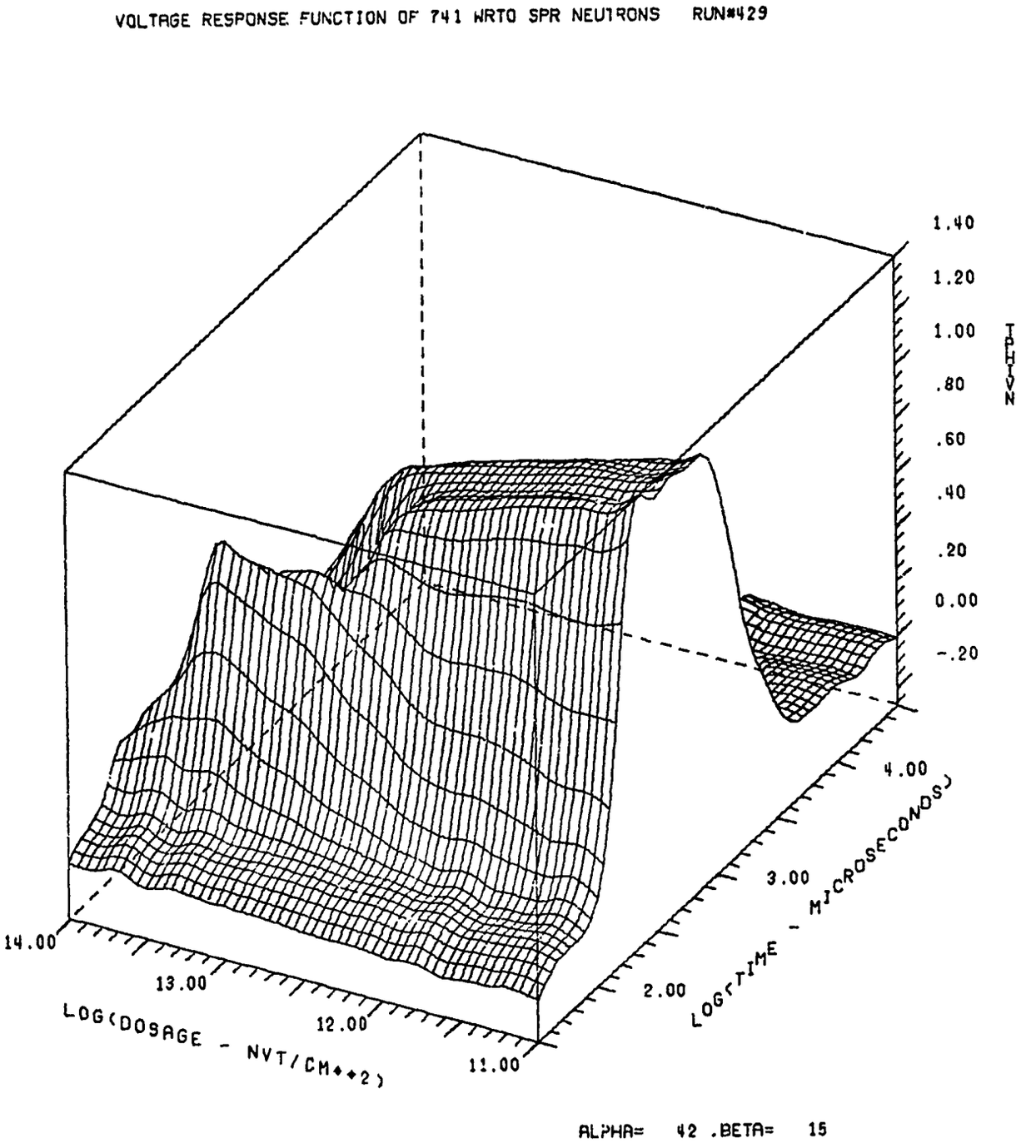


Figure 23a.

Figure 23. Voltage Response Function of 741 due to SPR Neutrons

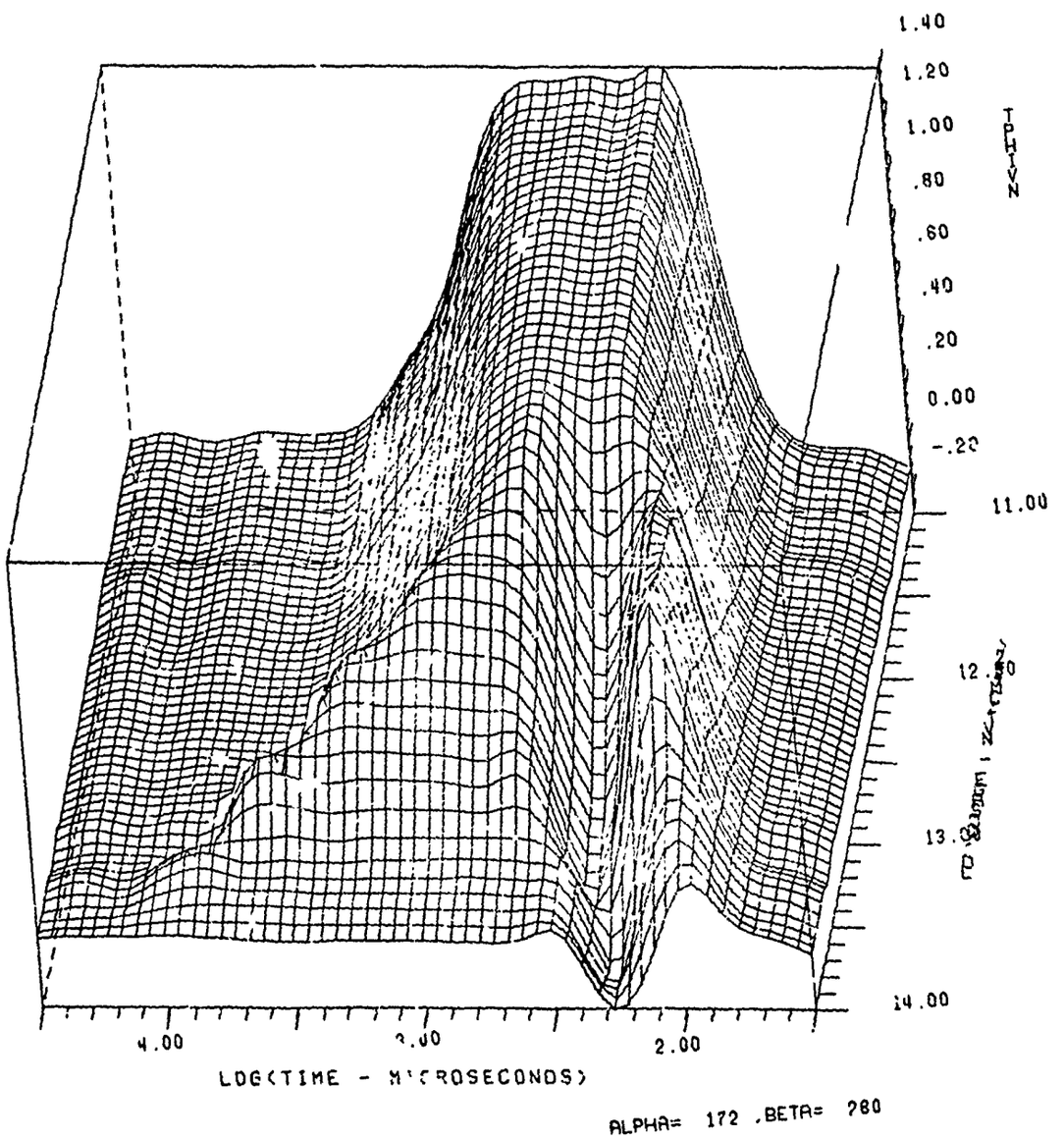

VOLTAGE RESPONSE FUNCTION OF 741 WRTC SPR NEUTRONS RUN#429
1.40
1.20
1.00
.80
.60
.40
.20
0.00
11.00
12.00
13.00
14.00
4.00
2.00
LOG(TIME - MICROSECONDS)
ALPHA= 172 .BETA= 280

Figure 23b.

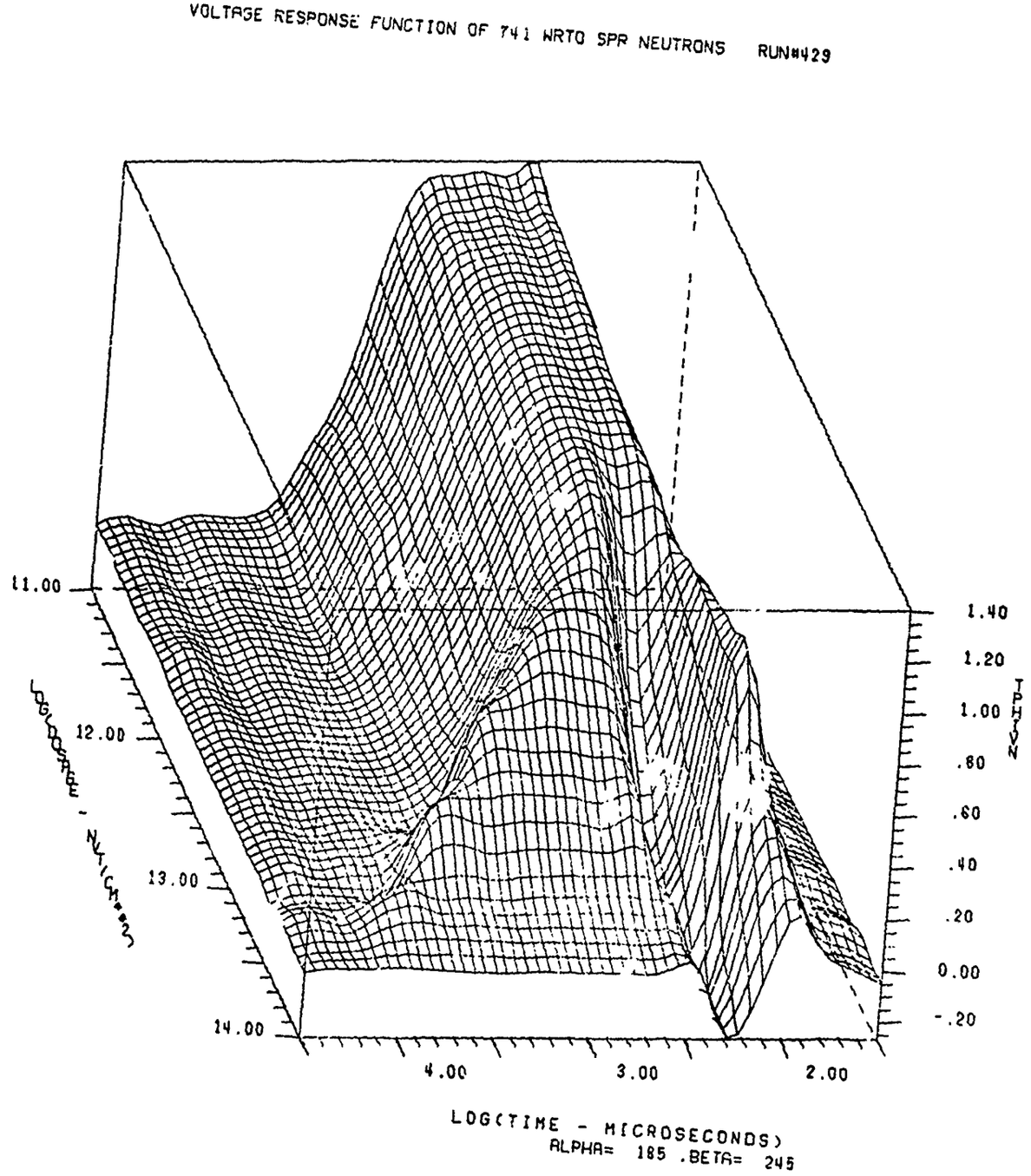

VOLTAGE RESPONSE FUNCTION OF 741 WRTO SPR NEUTRONS RUN#429
11.00
12.00
13.00
14.00
LOG(DOSAGE - NVICH=23)
1.40
1.20
1.00
.80
.60
.40
.20
0.00
-.20
IPHIVN
4.00
3.00
2.00
LOG(TIME - MICROSECONDS)
ALPHA= 185 .BETA= 245

Figure 23c.

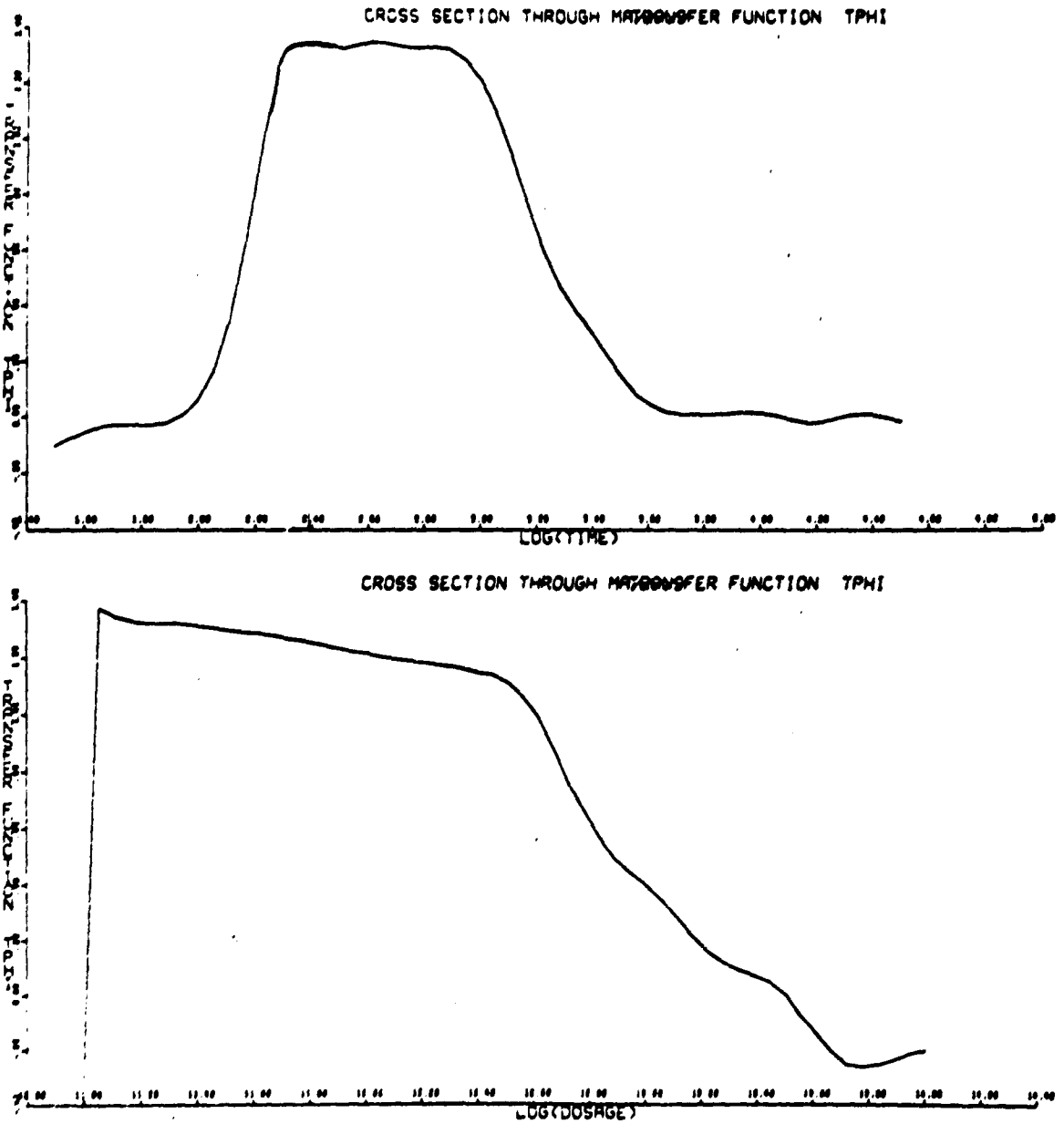
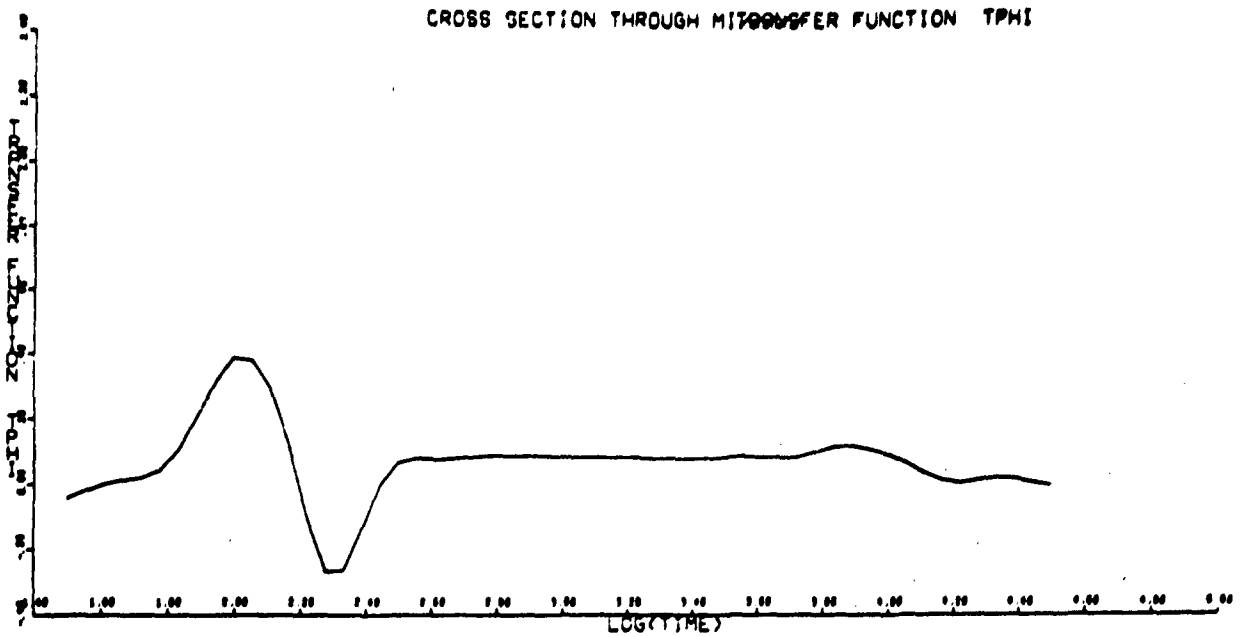


Figure 24a. Cross Section Through Maximum Transfer Function Value of the 741 SPR Surface of Figure 23



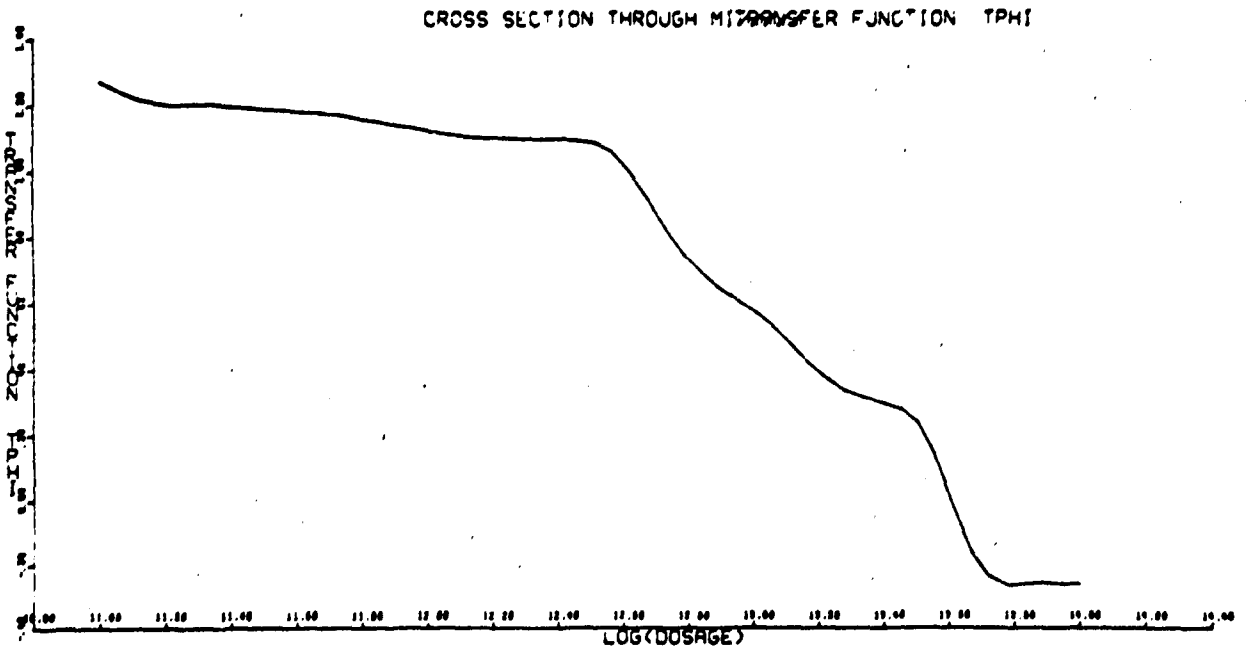


Figure 24b. Cross Section Through Minimum Transfer Function Value of the 741 SPR Surface of Figure 23

5. COMPUTER FITS TO THE 9704 ELECTRICAL AND RADIATION RESPONSE SURFACES

As discussed earlier, no hand drawings were prepared for the 9704 digital gate surfaces. The resolution of conflicting or sparse data available from the experiments was one problem in selecting and developing proper computer based strategies.

a. Electrical response surface

The gate electrical characterization was obtained with the circuit configuration shown in Figure 25, with data coming out as an x-y recorder tracing of the output voltage versus time for input pulses of various amplitudes and a fixed length of 300 ns. This 300 ns pulse length was sufficient for the steady state to be reached, particularly for the long time constant phenomenon that occur in the transition range. Then the output tracings were digitized and the data key punched as the ZDATA deck for FIT3D, with the results that are shown in Figure 26a, b, and c.

Some ringing is evident in the turn-on and turn-off of the device. The shortest possible lead-lengths in the test fixture were unable to eliminate the ringing. The values of circuit capacitance were far smaller than those required to explain the observed ringing frequency, and hence must be due to internal device capacitance. The figure shown made use of the linear interpolation option in FITIT to call INTERP so as to provide a denser packing of data points to control the "rolliness" of the cubics. This was needed in the fast transition regions. A further step necessary was to provide a line of data points along the t = 0 axis, to "tie down" the end of the surface. The experimental data supplies a multiple redundancy of points that are all located at the same spot, and hence the fitting polynomials are unconstrained elsewhere.

The essential manner in which the subroutine INTERP operates to provide additional data points to help in packing the data plane fully, is to first label legitimate data strings as .TRUE., and the new strings to be interpolated in between them as .FALSE. Next, a DO loop marches from one end of the y axis to the other interrogating the logical variable TYPE to find out if the string position is .FALSE. in which case it then locates the neighboring .TRUE. strings on either side. Next another DO loop moves along that .FALSE. string in the x direction by the desired amount. Then it finds four bracketing valid data points on the neighboring .TRUE. strings, and first interpolates along their x direction to find the

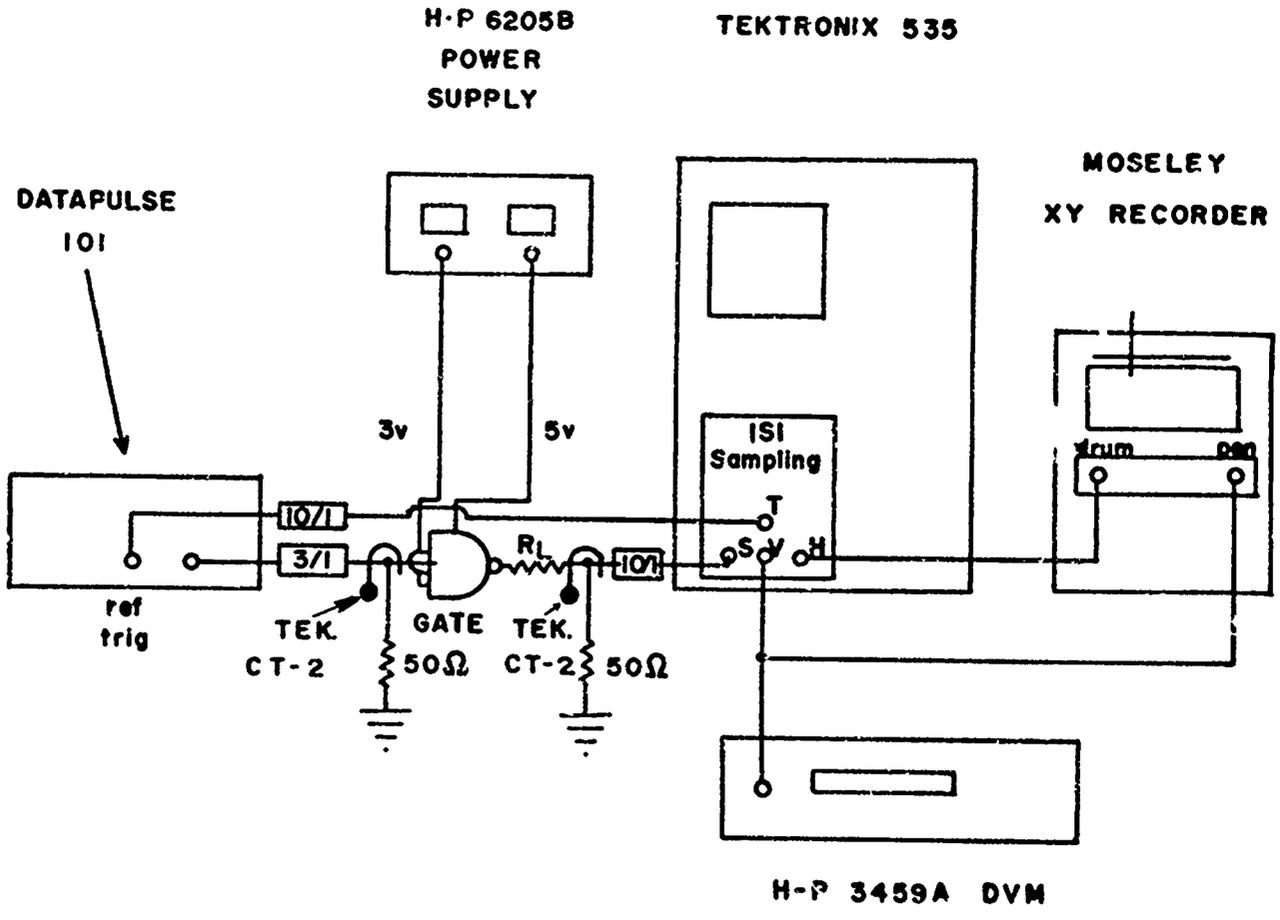


Figure 25. Electrical Characterization Circuitry for Digital Gate 9704, H-P Denotes Hewlett-Packard Instrument

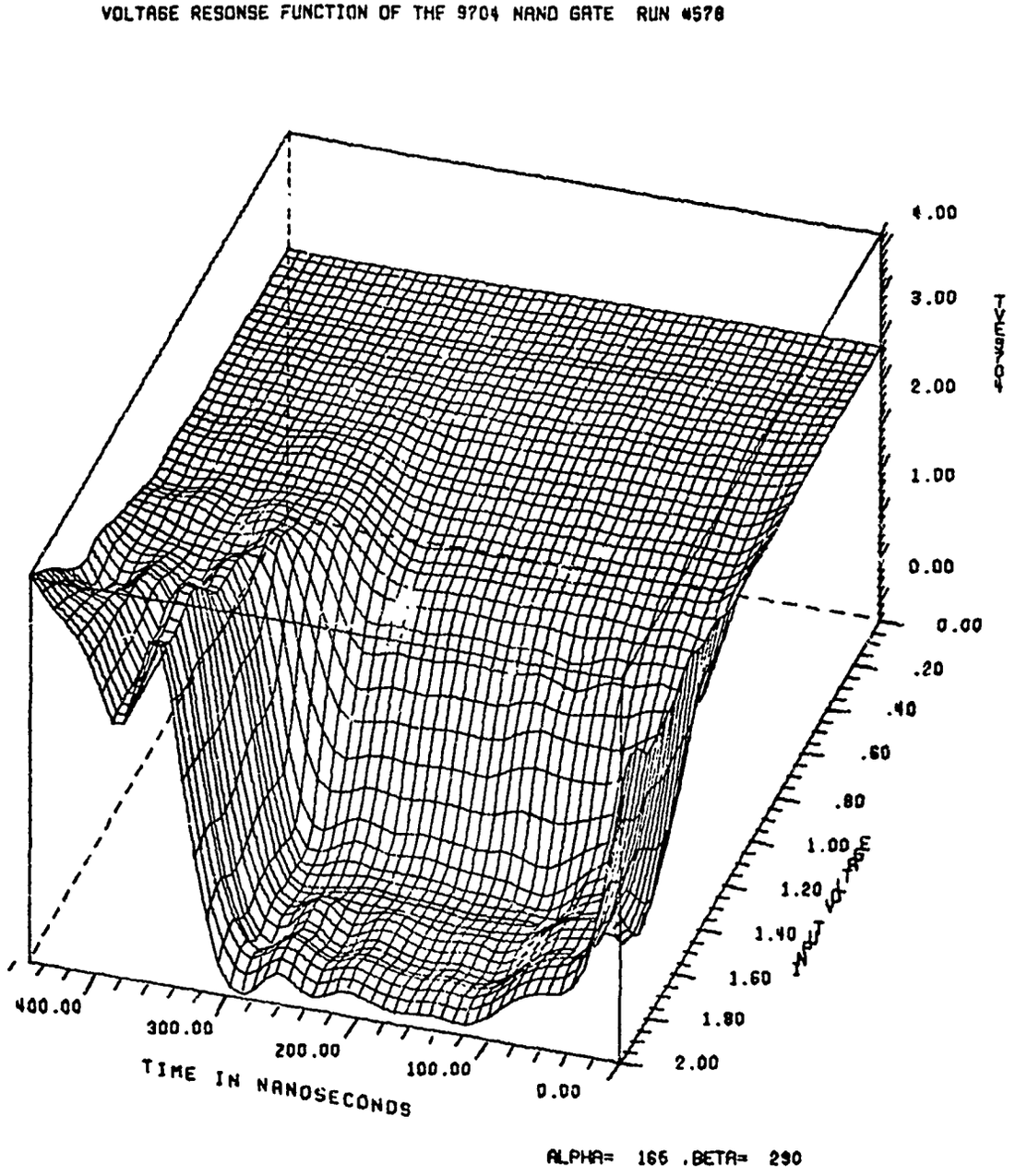


Figure 26. Voltage Response Function Surface of the 9704 NAND Gate

Figure 26a.

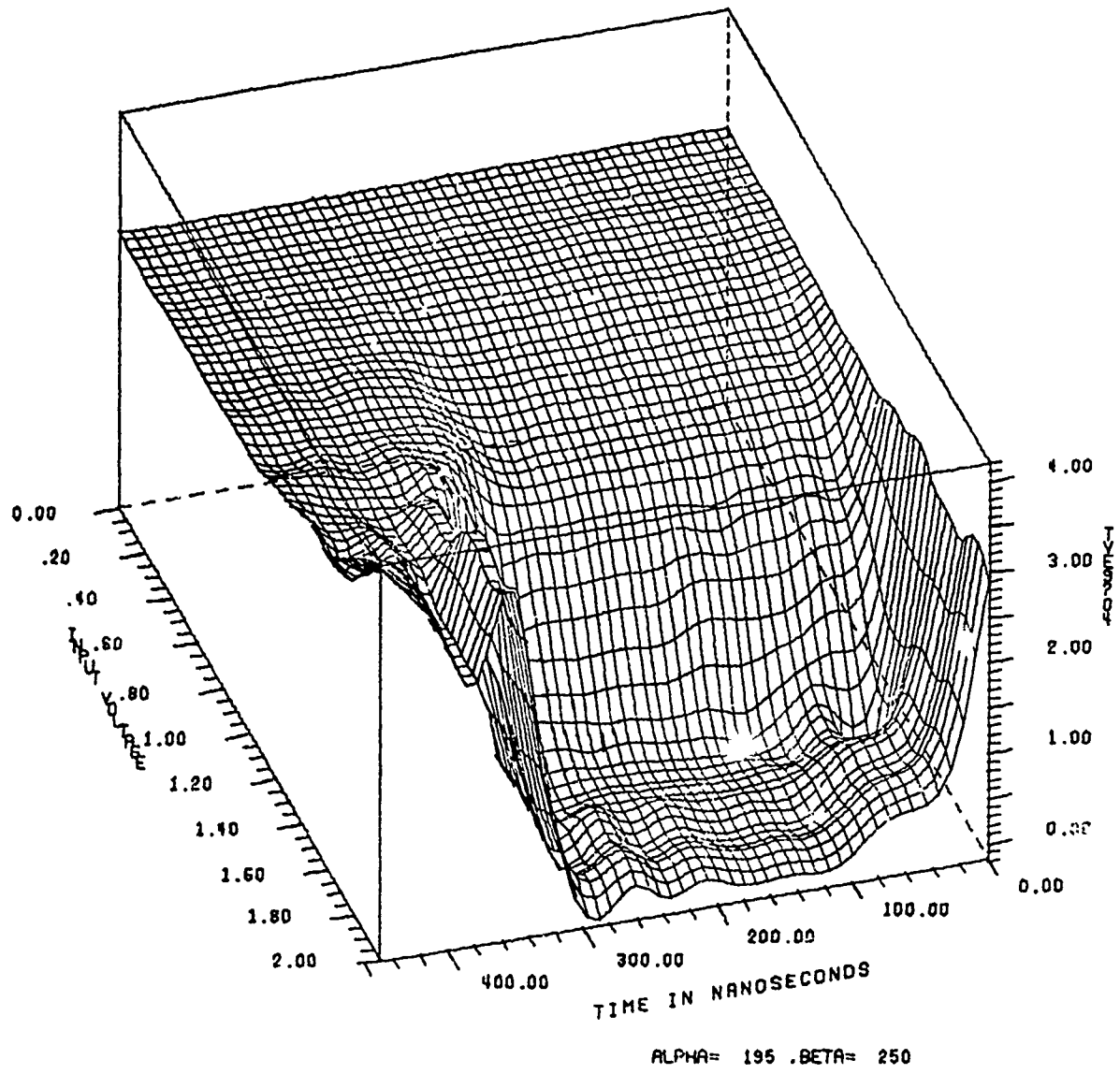

VOLTAGE RESONSE FUNCTION OF THE 9704 NAND GATE RUN #578
0.00
.20
.40
.60
.80
1.00
1.20
1.40
1.60
1.80
2.00
INPUT VOLTAGE
4.00
3.00
2.00
1.00
0.00
OUTPUT VOLTAGE
100.00
200.00
300.00
400.00
TIME IN NANOSECONDS
ALPHA= 195 .BETA= 250

Figure 26b.

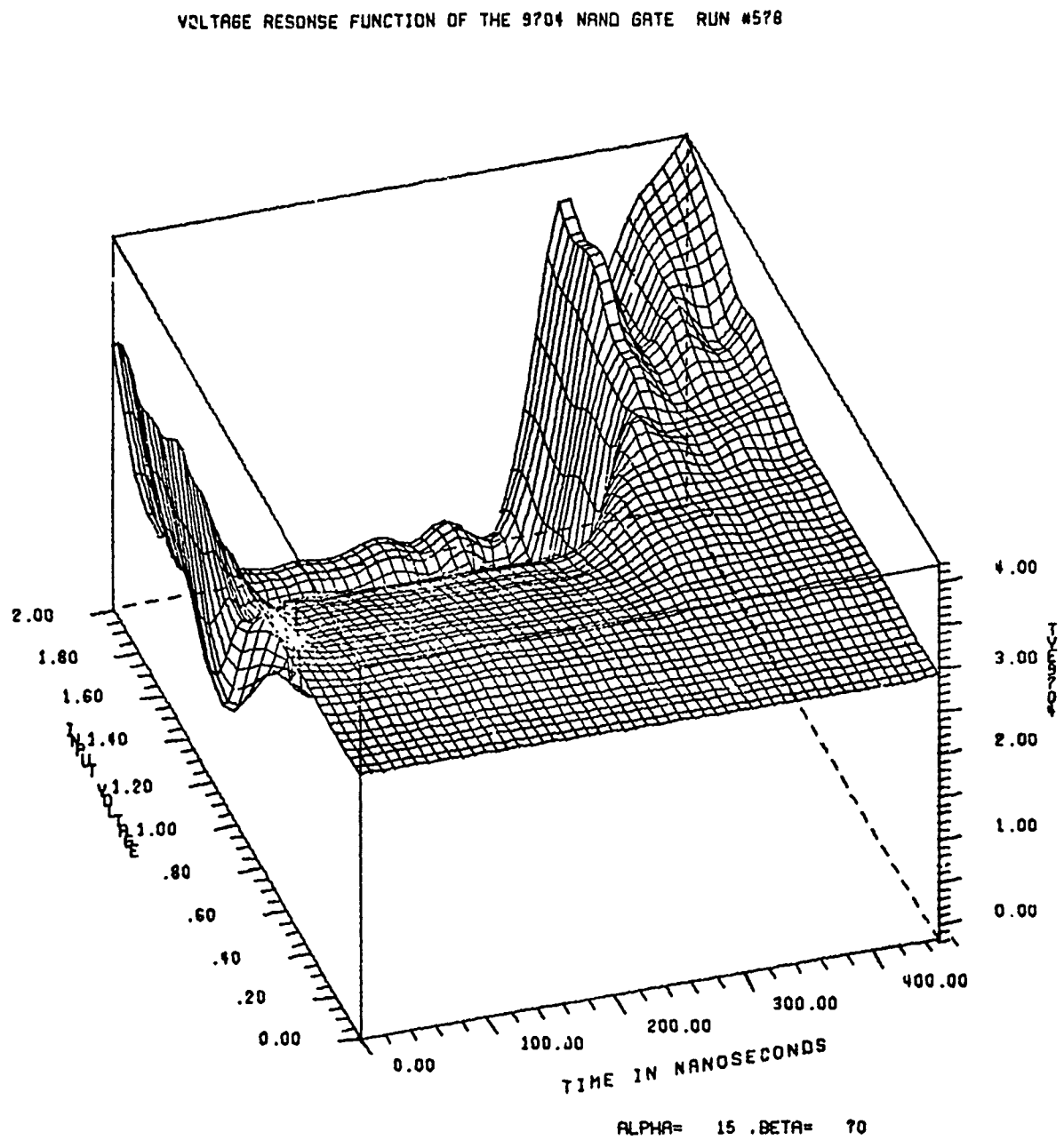
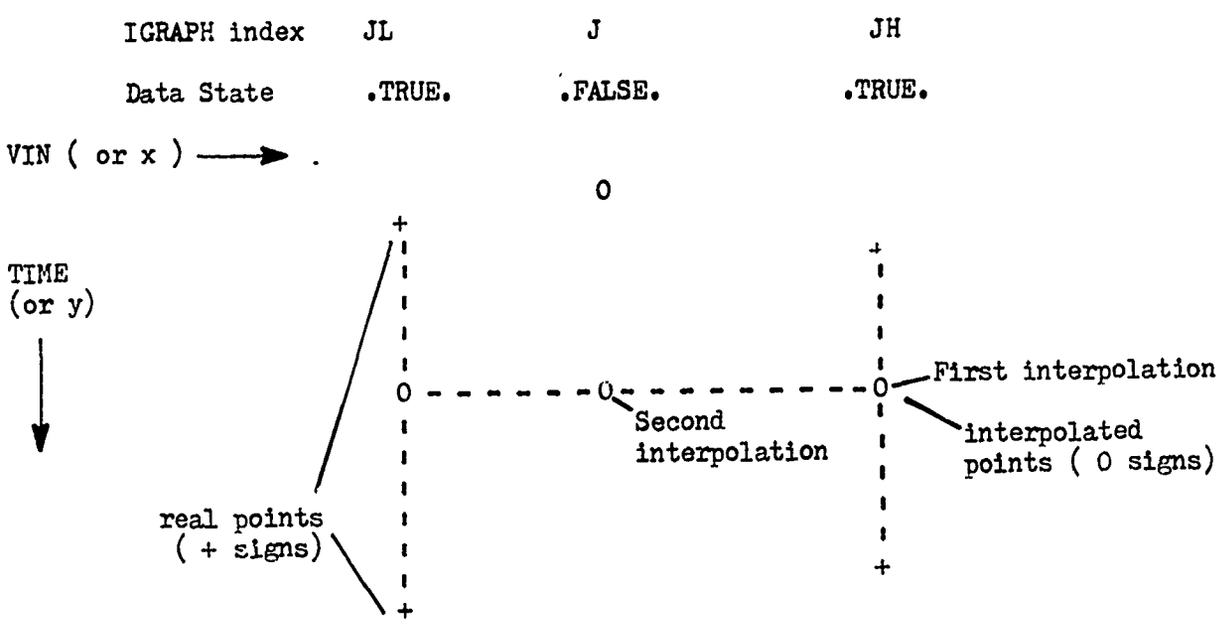

VOLTAGE RESONSE FUNCTION OF THE 9704 NAND GATE RUN #578
2.00
1.80
1.60
1.40
1.20
1.00
.80
.60
.40
.20
0.00
INPUT VOLTAGE
0.00
100.00
200.00
300.00
400.00
TIME IN NANOSECONDS
4.00
3.00
2.00
1.00
0.00
OUTPUT VOLTAGE
ALPHA= 15 .BETA= 70

Figure 26c.

z value at the same x coordinate as the new .FALSE. point. This finds two points on either side of the new point. Then linear interpolation is used again between these two points on the .TRUE. strings to find the z value at the new .FALSE. point. The DO then continues on to the next desired .FALSE. point and repeats the process. If the data could be instantaneously processed as it is acquired, the need for this type of processing would be minimized, since the sparseness of data is very evident in the results of the fitting process.



Sketch of Double Interpolation Method Used for Filling Data Plane

b. Neutron response surfaces

The voltage and current response surfaces of the gate presented a new class of problems in the process of deriving a satisfactory result. To fully describe these problems, we shall include herein the full sequence of plots from the first try to the last. We will not delete our mistakes since it is from those that the successful strategies frequently are formed. Both the voltage and current radiation response surfaces will be discussed concurrently rather than separately to show how they presented similar problems.

The initial fit and plot of the radiation neutron current transfer function for the gate is shown in Figure 27, while that of the voltage surface is shown in Figure 28. Very evident in both of them is the large, smooth region at very

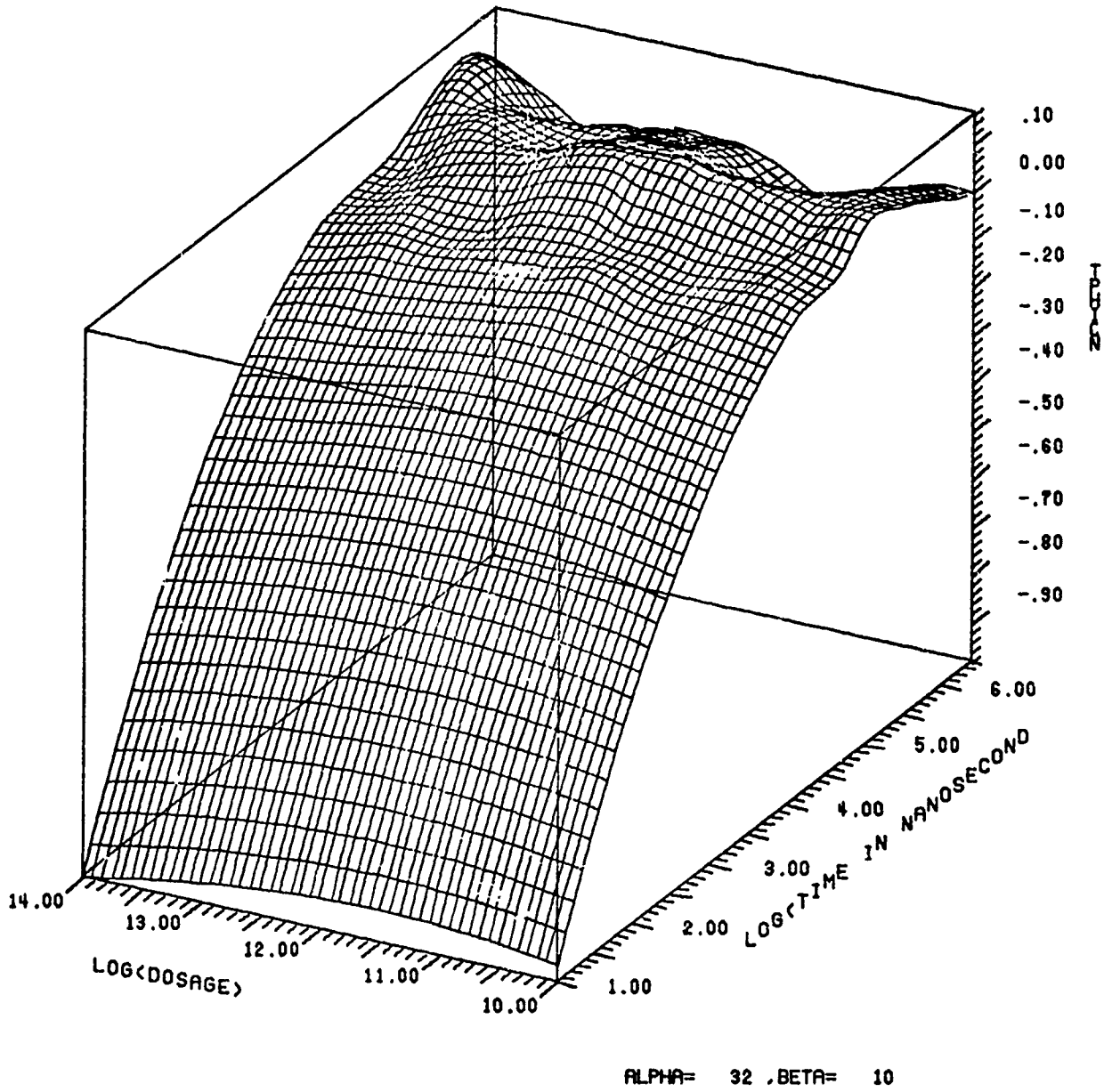


Figure 27. Current Neutron Function of 9704 NAND Gate, First Fitting of Basic Data by Computer

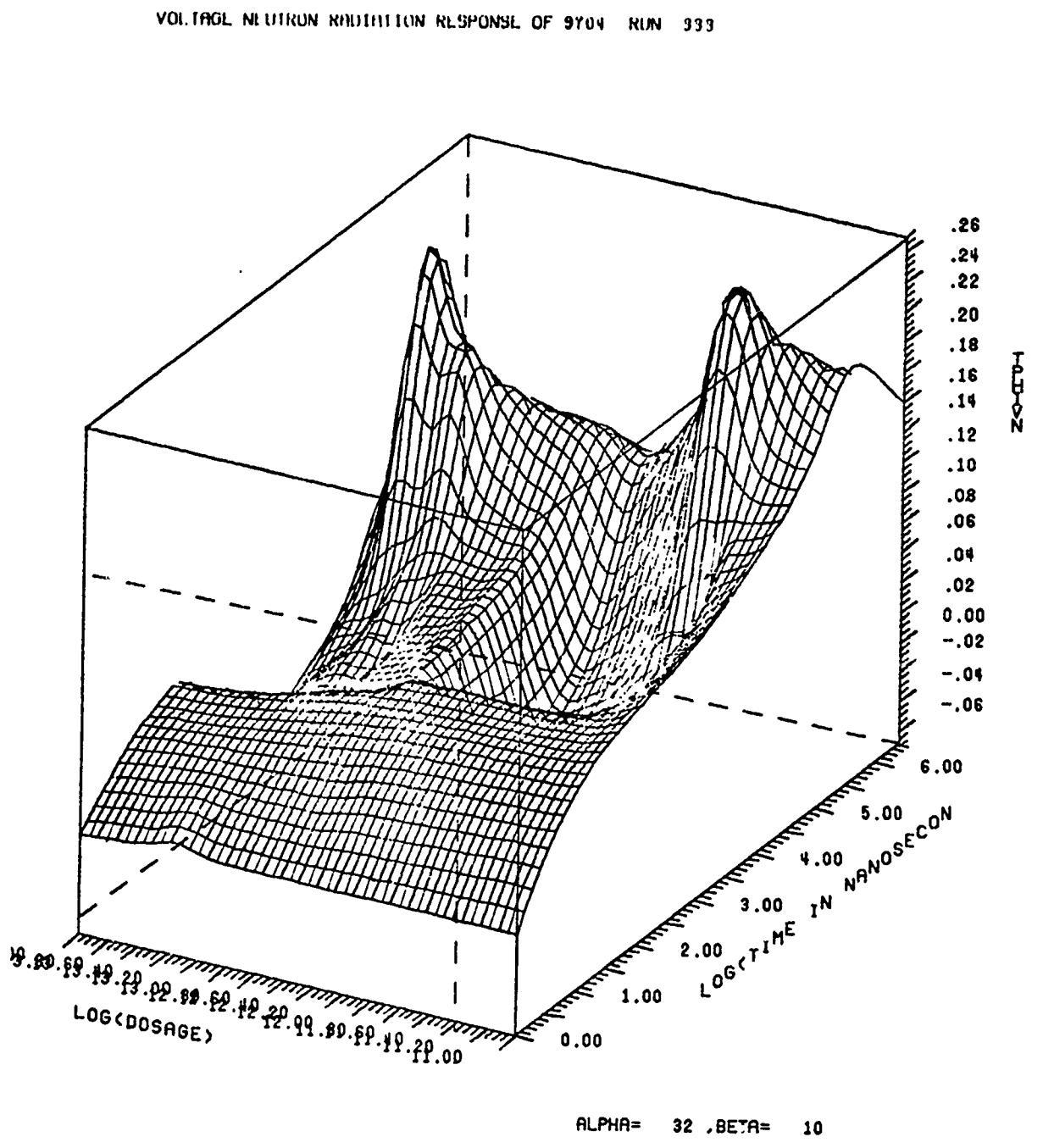


Figure 28. Voltage Neutron Radiation Response of 9704, First Fitting of Basic Data by Computer

small time values. In both cases this is entirely spurious, and is the result of a mistake in specifying the lower limit for the time axis over which the routine FITIT was to generate the machine fit. The initial value of time in the experimental data (Polaroid photographs of CRT tracings) is the trigger of the reactor core and the oscilloscope sweep. As discussed in the Appendix the build-up of fission processes in the reactor core occurs exponentially in time reaching a maximum the order of a hundred microseconds after trigger. Meaningful excursions from the vertical zero on the scope tracing do not begin until about 15 or 20 ms after trigger. The error in the fit was to use a value of the variable XLOW which was too small, 0.0 or 1.0, on the log time scale, rather than 3.0 (which corresponds to 1 ms). Hence, a very large portion of the basic x-y fitting grid plane had no data points to constrain locally the fitting function, which was then free to minimize residuals in the spline sense in those areas containing data. The result is the long downward sweep in the current surface which is entirely erroneous.

The next try at the current neutron transfer function is shown in the results of run 322 in Figure 29. Despite all the lumps and wiggles, this is not a bad representation of the real data. The one spurious aspect is the negative excursion somewhere, as evidenced by the fact that the surface seems to be sitting in mid-air in the plot cube. So we turned the surface around in the view of run 328 as seen in Figure 30, which shows the backside of the hill. The negative excursion at a dosage of 10^{11} and 10^{13} is due to an absence of constraining data in those areas. By examining the basic data, filling in additional data points by hand where needed, and running through INTERP, the results of run 404 were obtained as shown in Figure 31. Still the surface does not seem really acceptable in that we don't expect experimental functions to be that rough.

The next try at the neutron-voltage transfer function gave the plot of run 342 shown in Figure 32a, where INTERP was used to fill in regions in the right hand data space. The vast difference between this figure and Figure 28, came about by deleting one valid data string from the collection of data. Of seven pictures representing dosages less than 10^{13}, only one showed any response, the rest were zero. Thus, it was necessary to use judgement and arbitrarily delete that one. Here it is evident that there is a threshold type of radiation response for the gate. Except for the one device, there was no effect of the radiation on

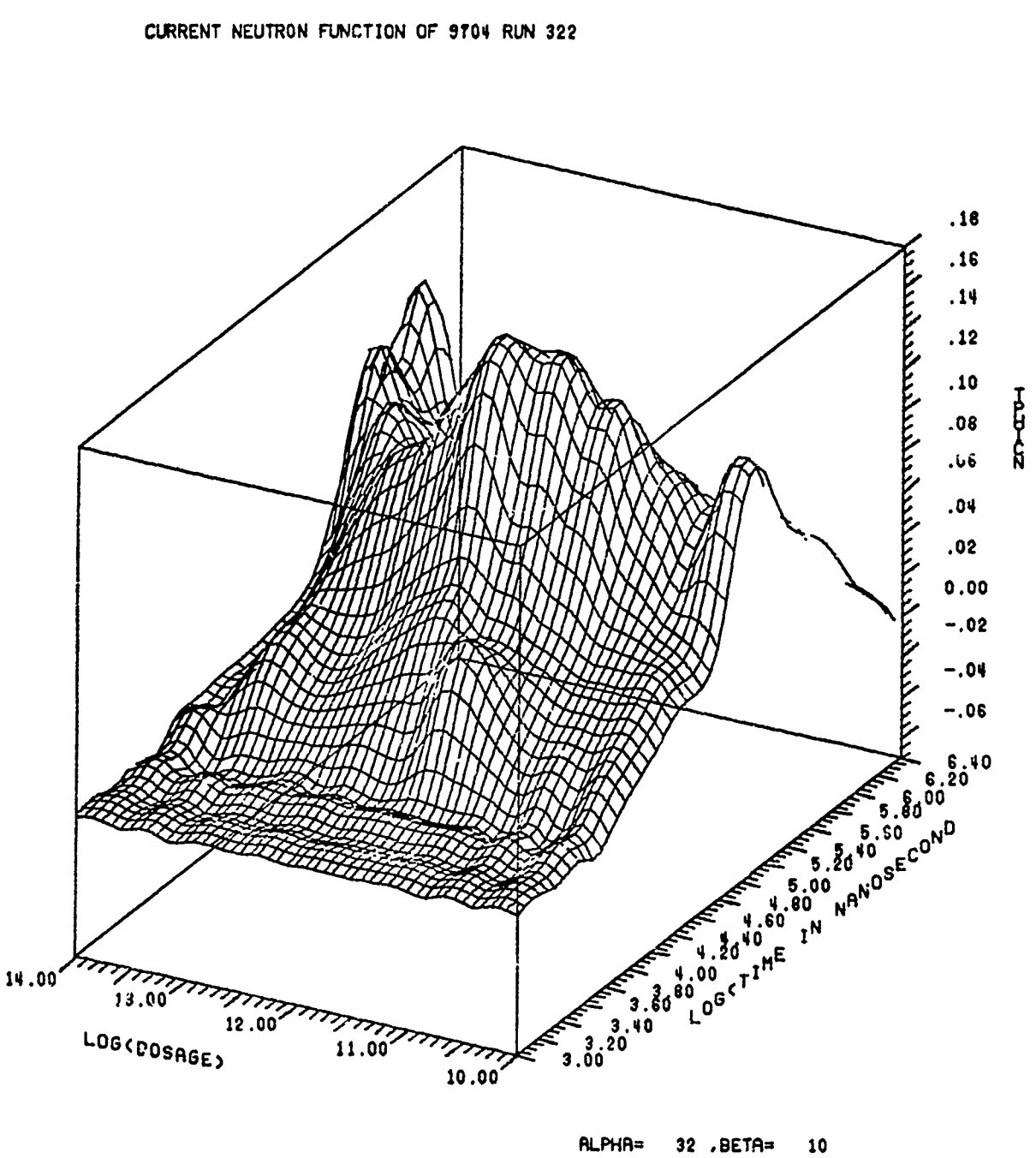


Figure 29. Front View of Current Neutron Function of 9704, Second Fitting by Computer

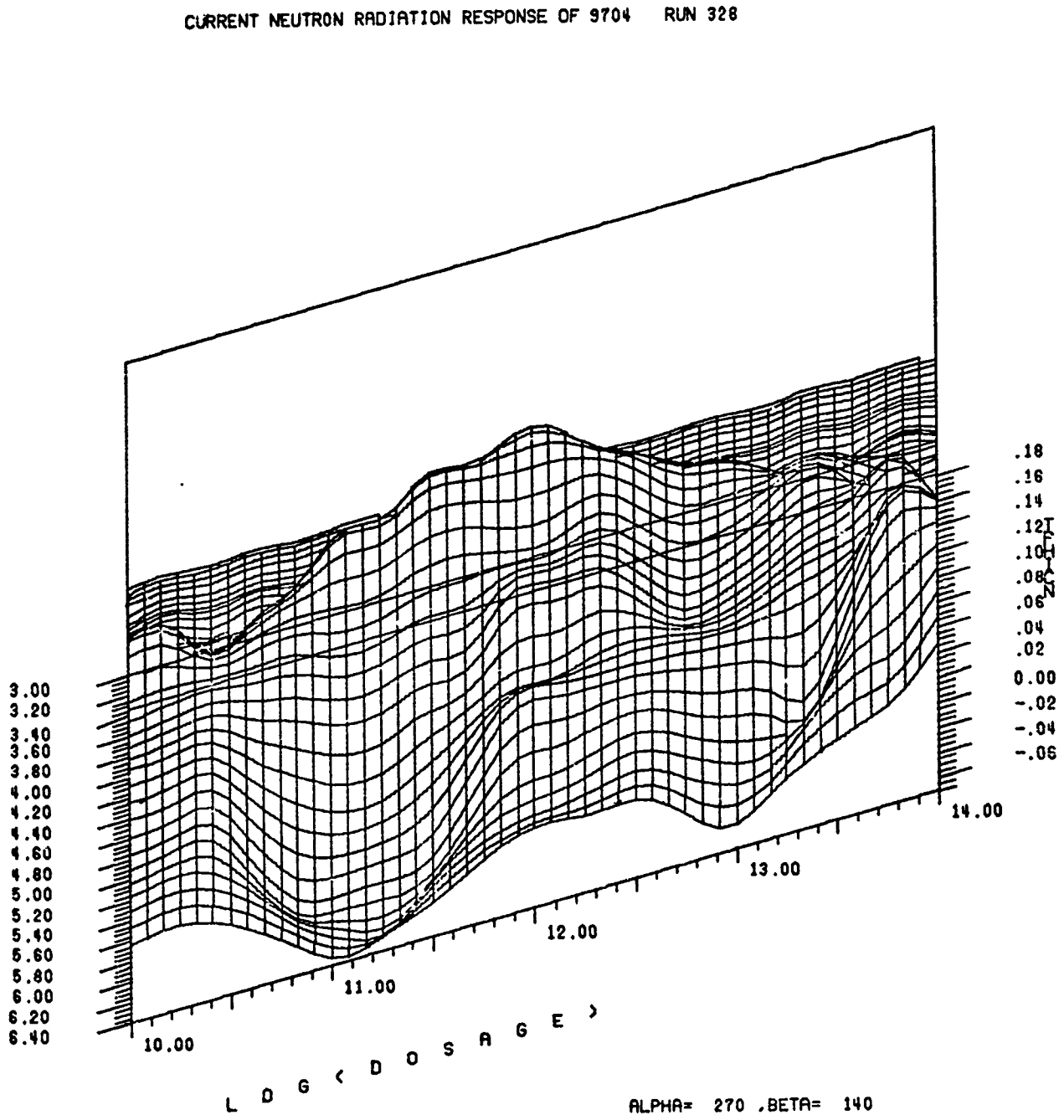


Figure 30. Rear View of Current Neutron Function of 9704, Second Fitting by Computer

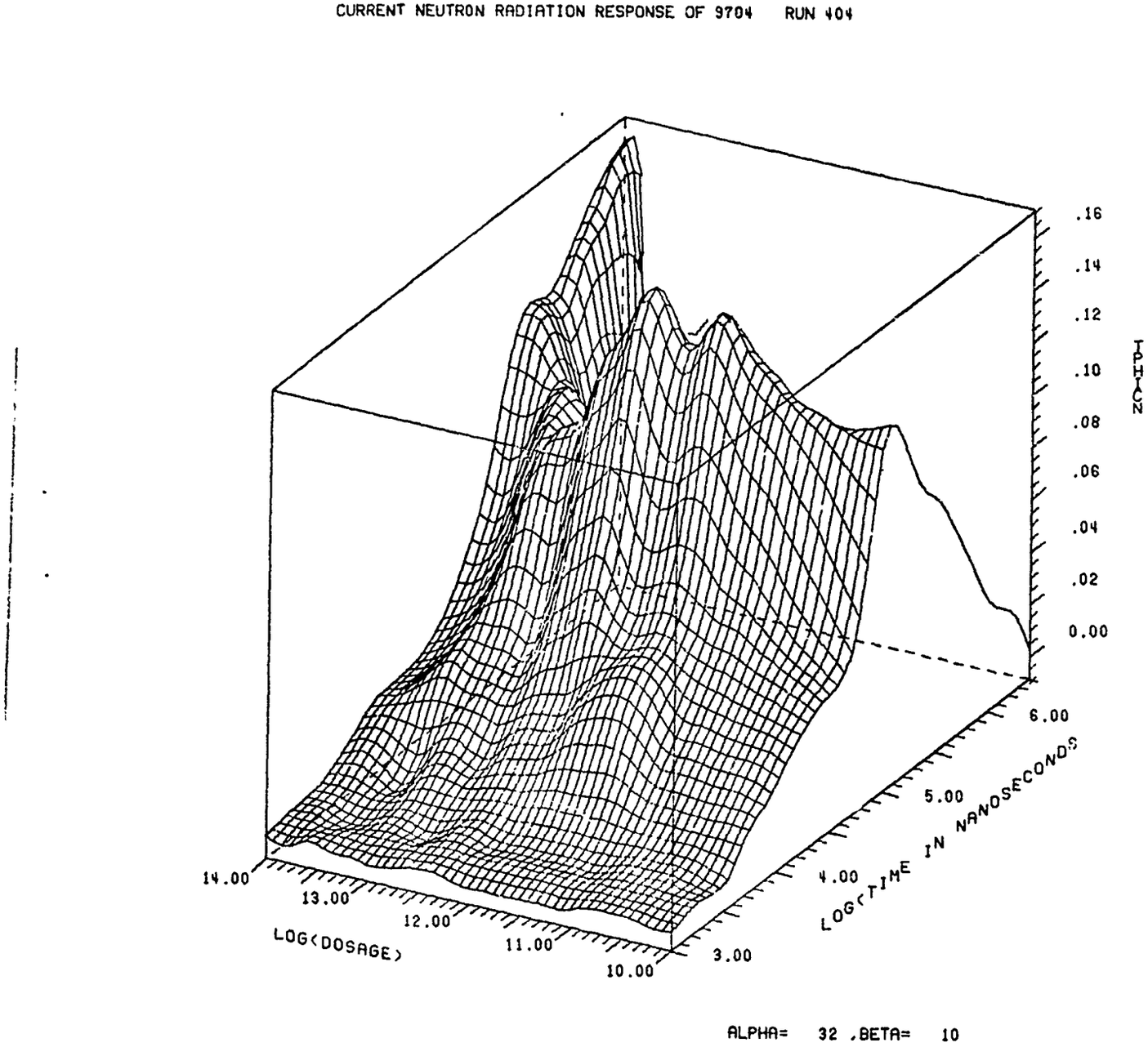


Figure 31. Front View of Current Neutron Function of 9704. Third Fitting by Computer

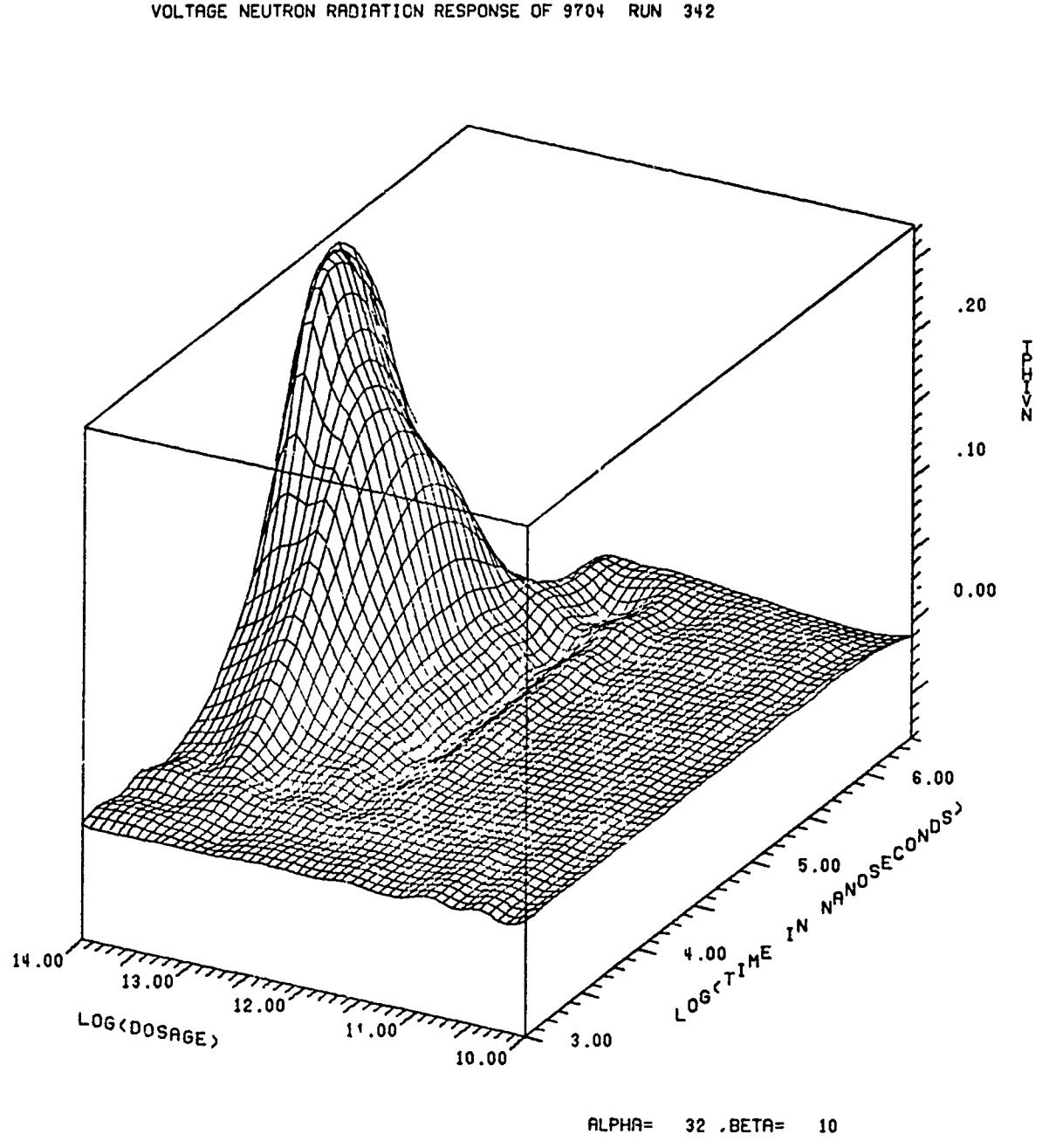


Figure 32a. Front View of Voltage Neutron Radiation Response of 9704. Second Computer Fitting

the output voltage until the dose exceeded about 10^{13} nvt/cm^2. The fact that the surface is sitting up in the plot cube shows again a negative swing is present somewhere. The other perspective views of Figure 32 b, c, and d, indicate a negative swing at maximum dose and time. This again was due to a sparseness of real data at that location. The final version of the surface after filling the corner with sufficient data values is shown in the results of runs 467 and 471 in Figure 33 a, b, and c. It should be realized that the radiation pulse drives the output voltage up, even though the output may already be in the electrically high digital state. Moreover, the output can swing higher than the positive supply voltage.

Now let us return to the current neutron transfer function surface to see how the smoothing routines were applied to try and even out the local inhomogeneities. The smoothing operations are an optional path in FITIT involving calls to the following subroutines:

NICER - sets up smoothing calls. First smooth on x, stepping along y; then smooth on y, stepping along x. Next, average the z values for the two smoothing directions. The number of passes is NTIME. NICER then calls

SMOOTH - handles setting up wild-pointing, differentiating, smoothing and array interchanges for

DUZ2 - performs actual operations. DUZ2 has options for anchoring of end points.

The starting point for the operations was the surface as shown in Figure 31 from run 362 and Figure 35 from run 362. Successive odd numbered passes on the front of this surface are shown in Figure 36 a through f, and the rear portion in Figure 37 a through f. The number of the smoothing pass is indicated by the SP abbreviation in the caption. The results were plotted to see actually what eleven smoothing passes mean to a surface. It is evident that a reasonably acceptable surface is achieved after three passes, and certainly by five. After that the smoothing hardly changes the basic structure. It is interesting to note how the deep valley on the back portion of the surface at log(dosage) = 13.55 is eventually eliminated by successive smoothing passes. The criteria telling us when enough smoothing has been performed is essentially subjective. However a more

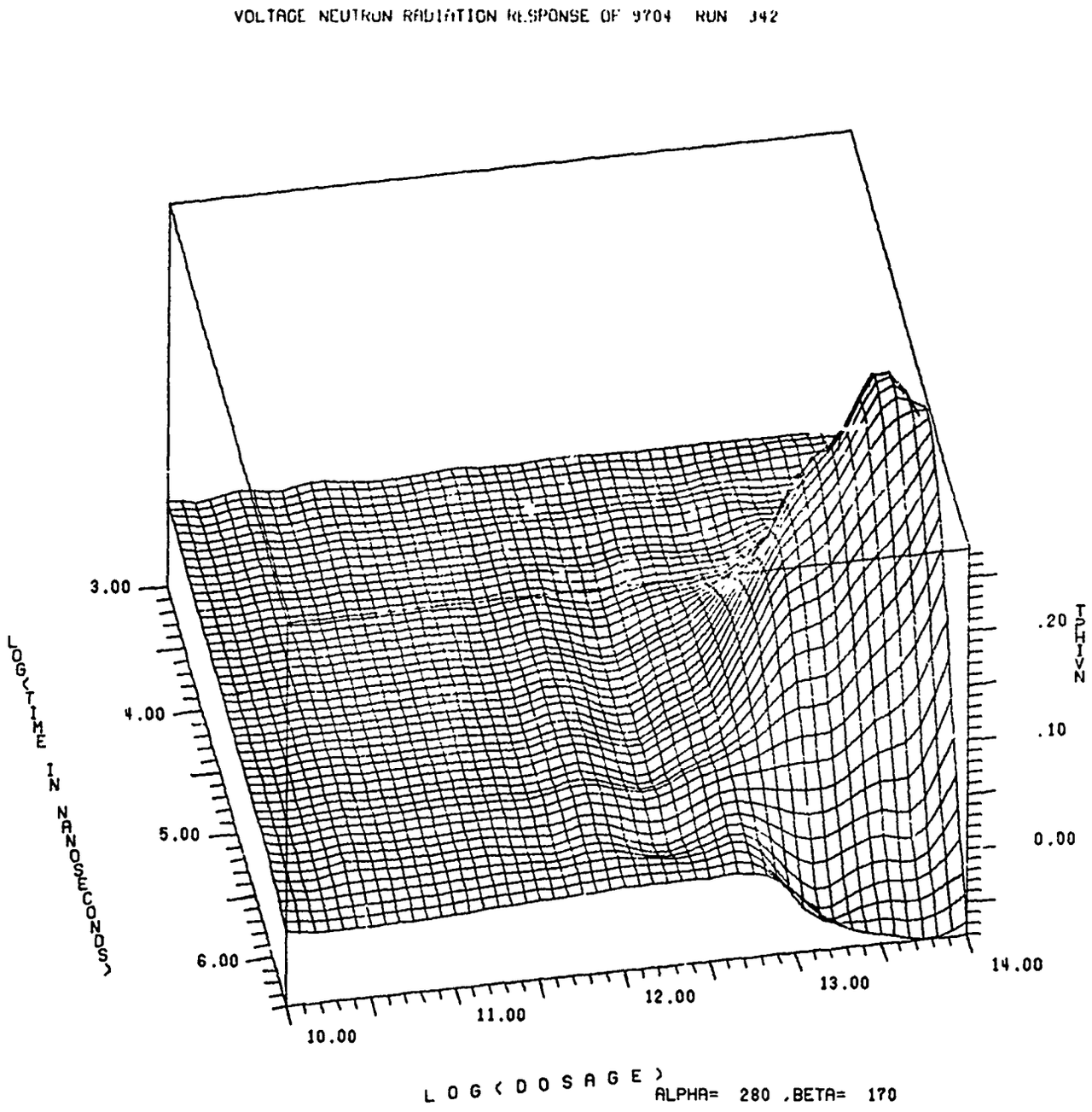


Figure 32b. Rear View of Voltage Neutron Radiation Response of 9704, Second Computer Fitting

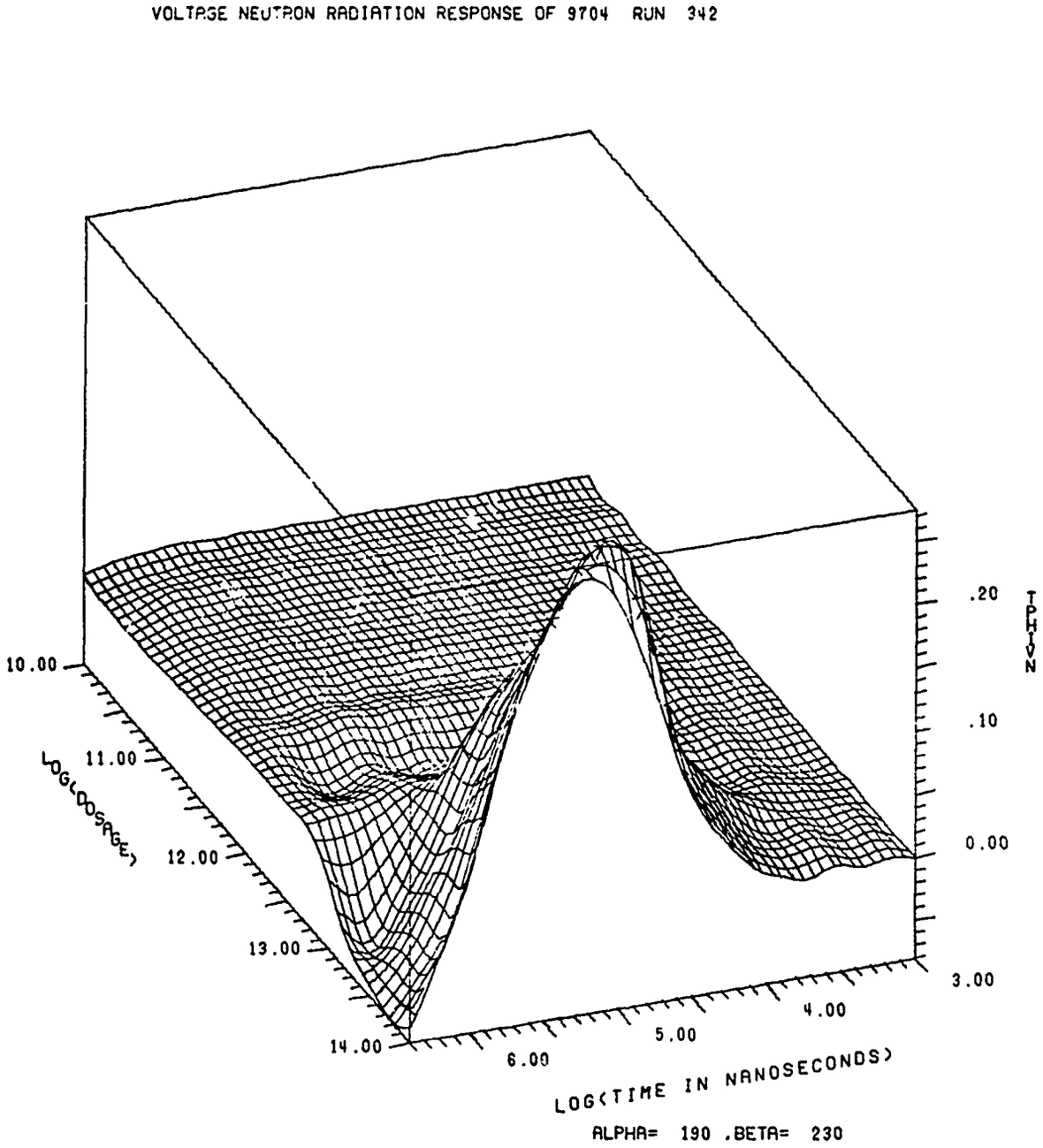


Figure 32c. Back Side View of Voltage Neutron Radiation Response of 9704. Second Computer Fitting

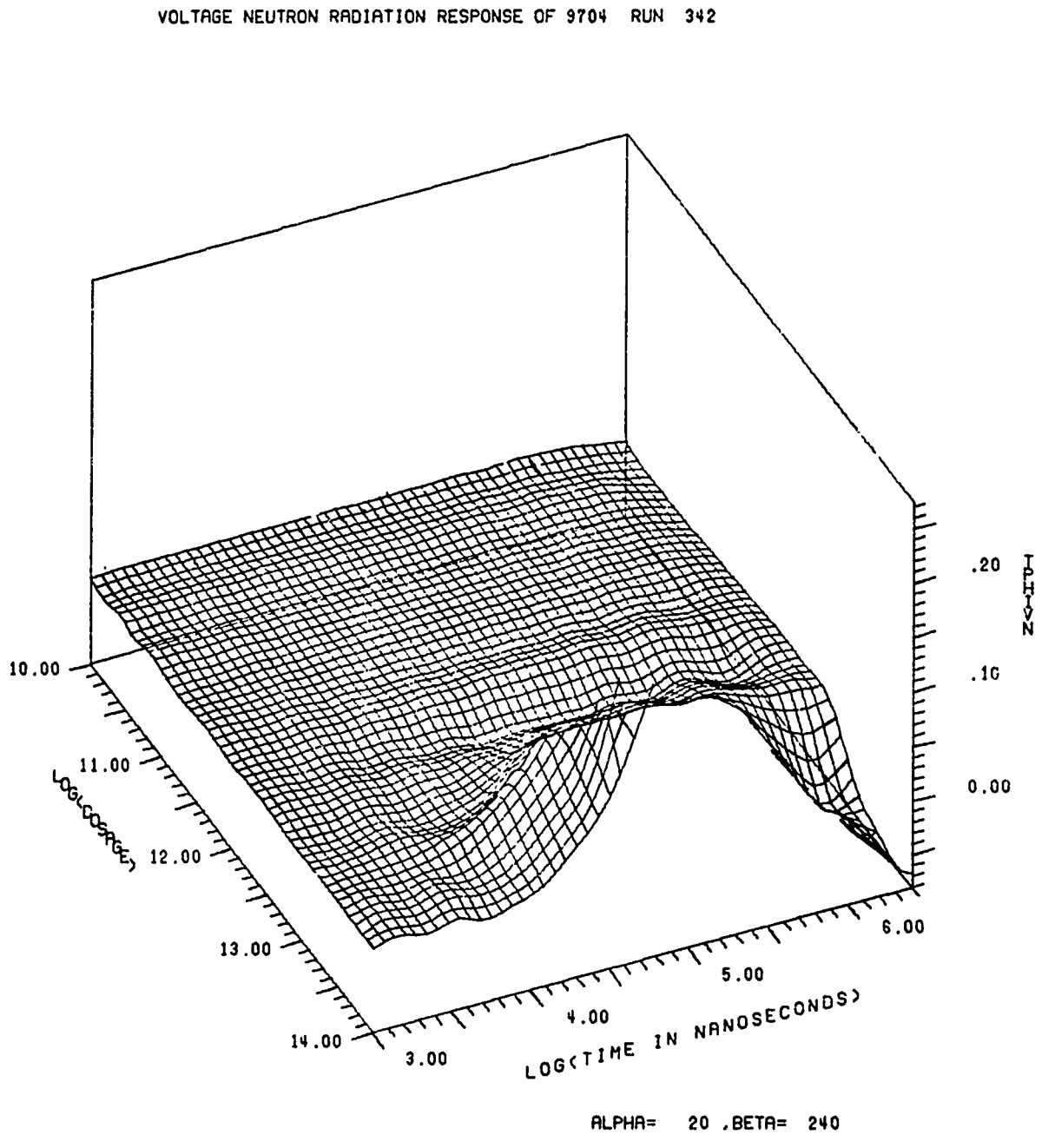


Figure 32d. Bottom View of Voltage Neutron Radiation Response of 9704, Second Computer Fitting

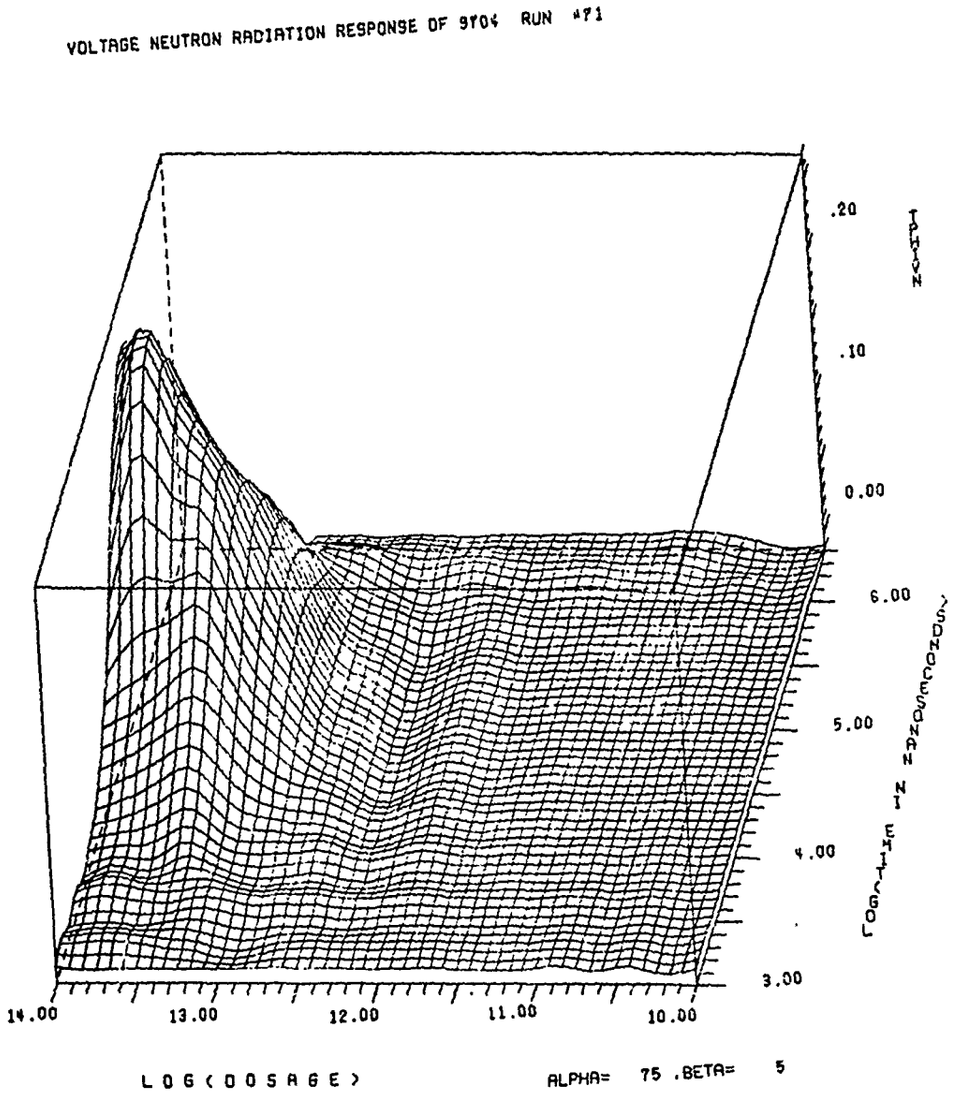


Figure 33a. Front View of Voltage Neutron Radiation Response of 9704, Third Fitting by Computer

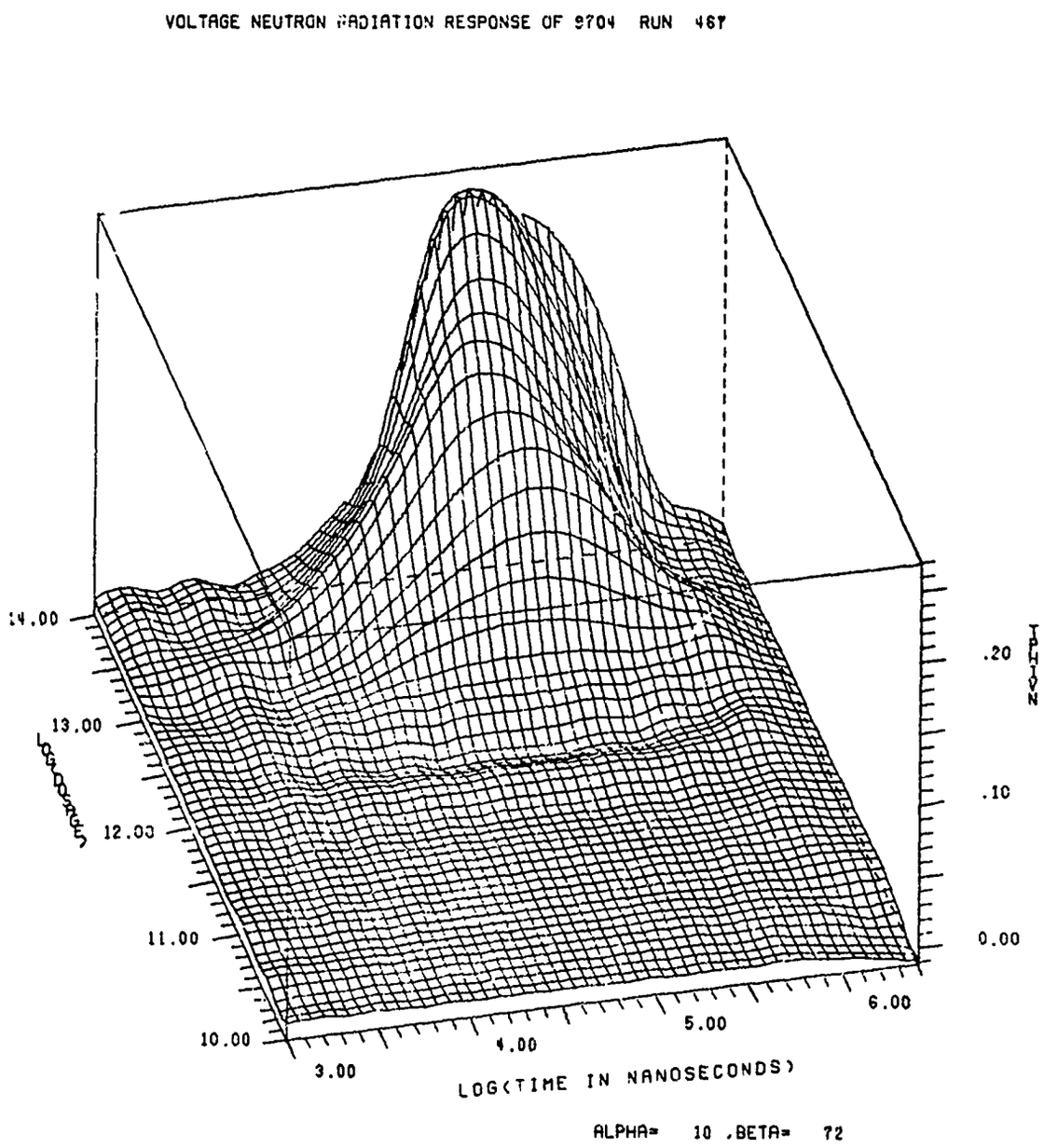


Figure 33b. Side View of Voltage Neutron Radiation Response of 9704, Third Fitting by Computer

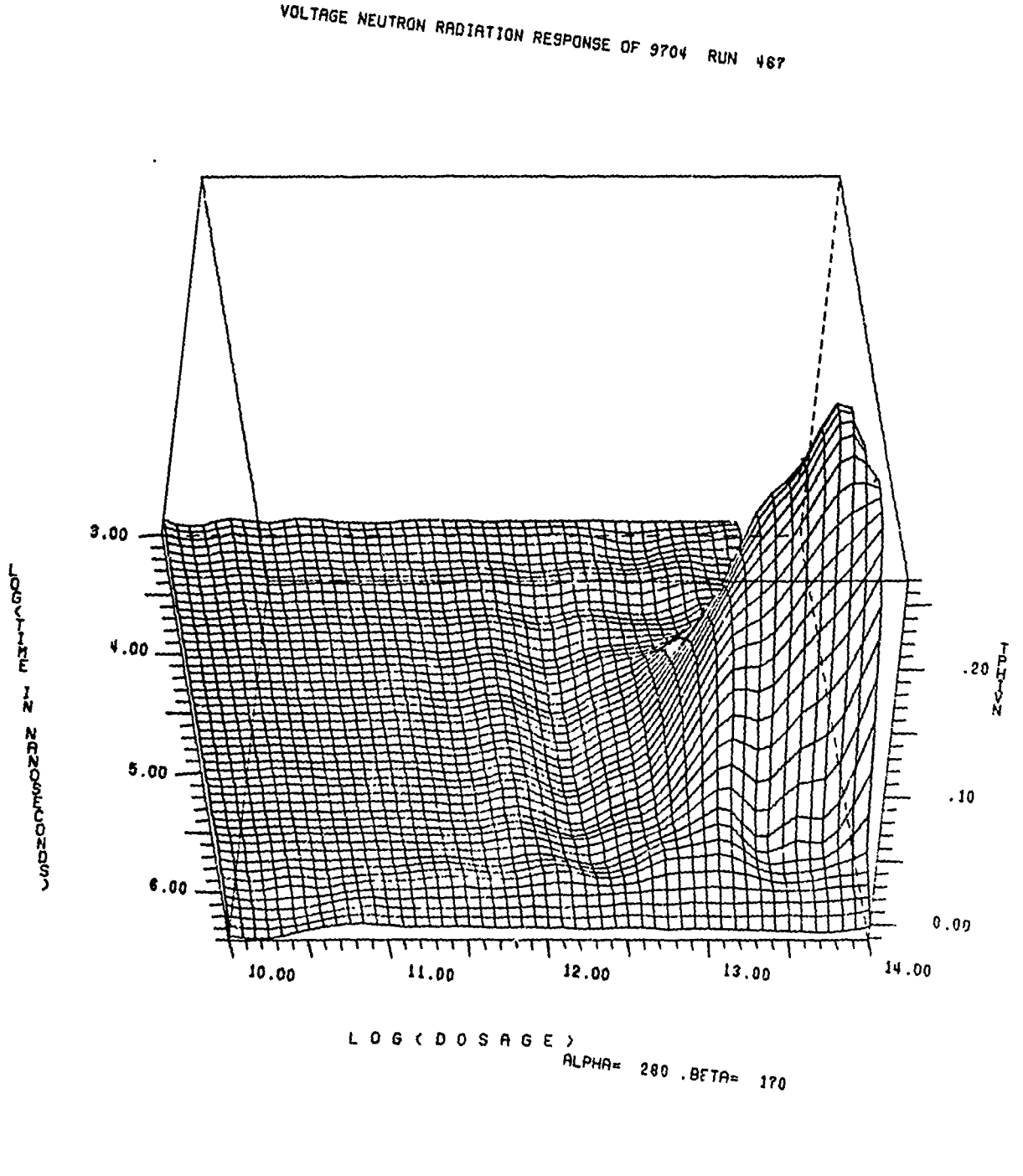


Figure 33c. Back View of Voltage Neutron Radiation Response of 9704. Third Fitting by Computer

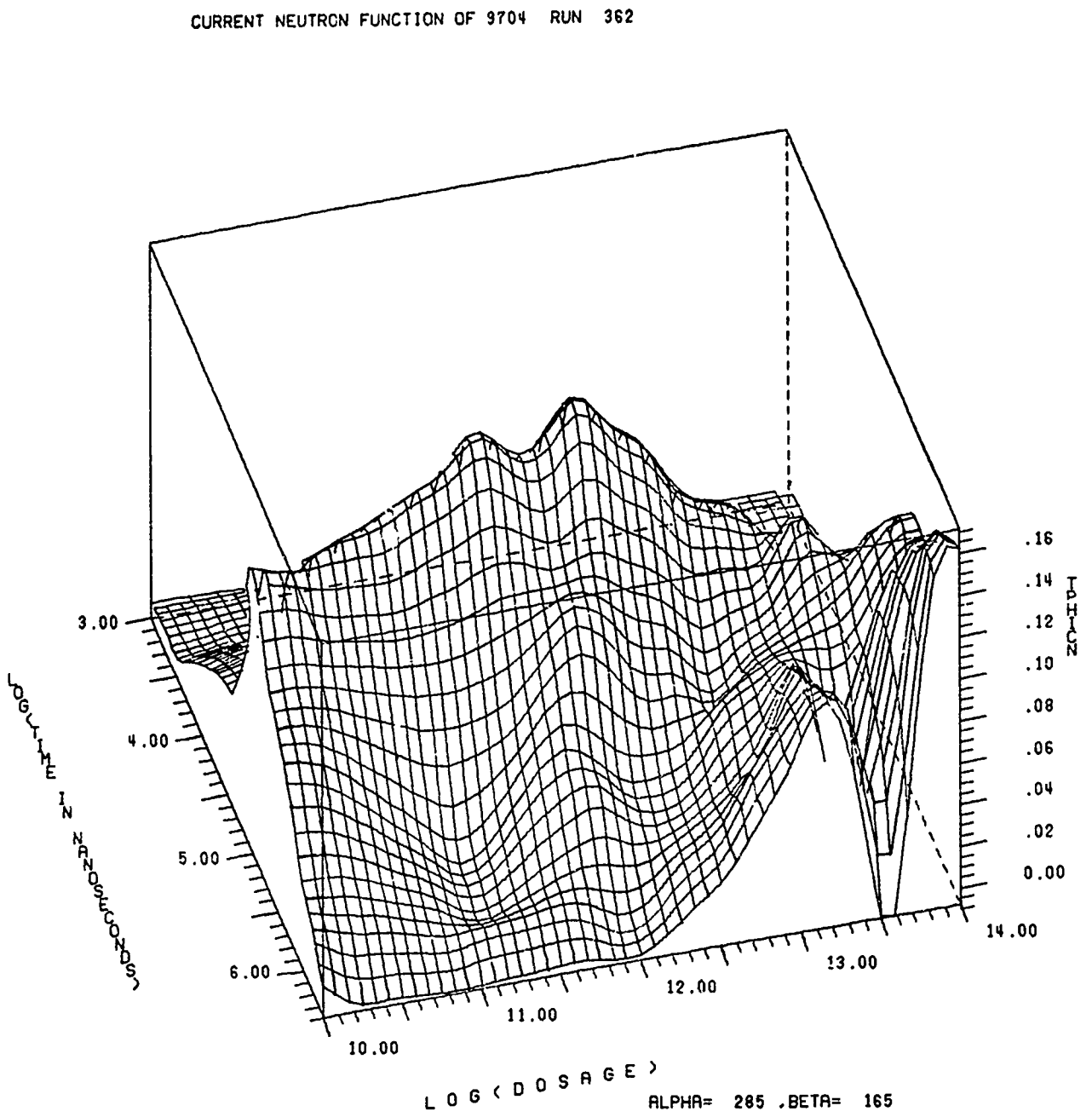


Figure 34. Rear View of Current Neutron Function of 9704. Second Fitting by Computer

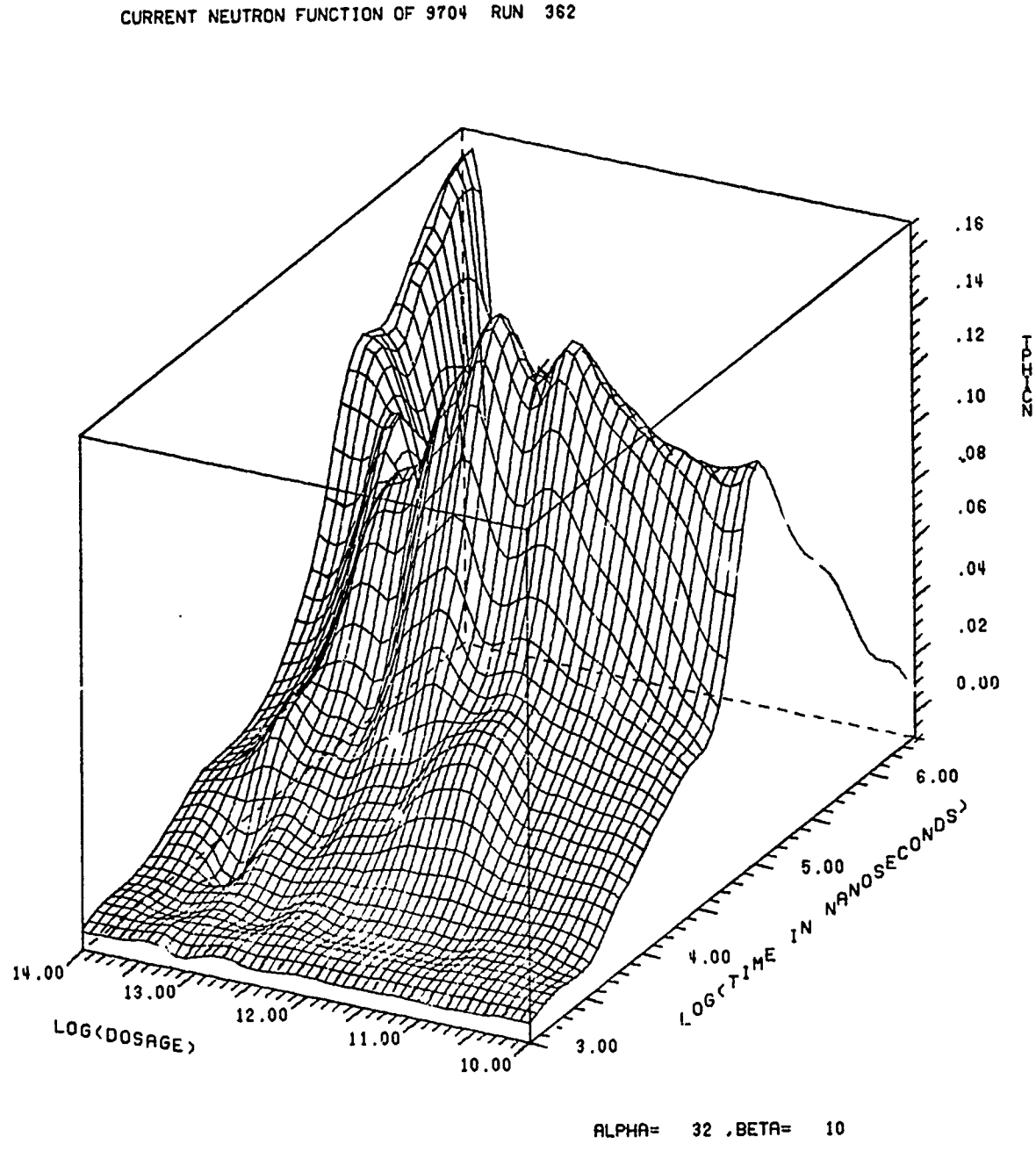


Figure 35. Front View of Current Neutron Function of 9704. Prior to Computer Smoothing

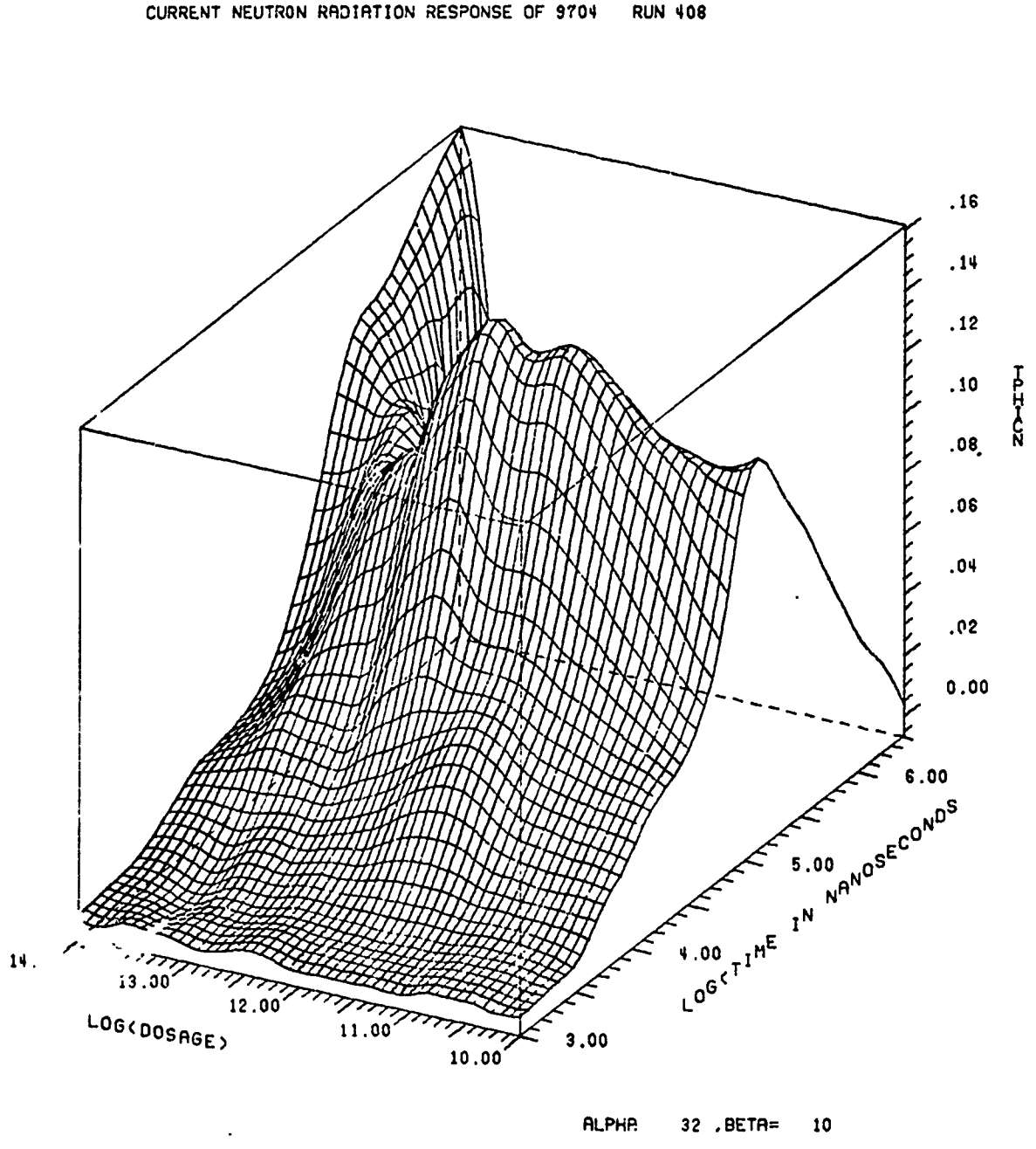


Figure 30a. Front View of Current Neutron Radiation Response of 9704, After One Smoothing Pass

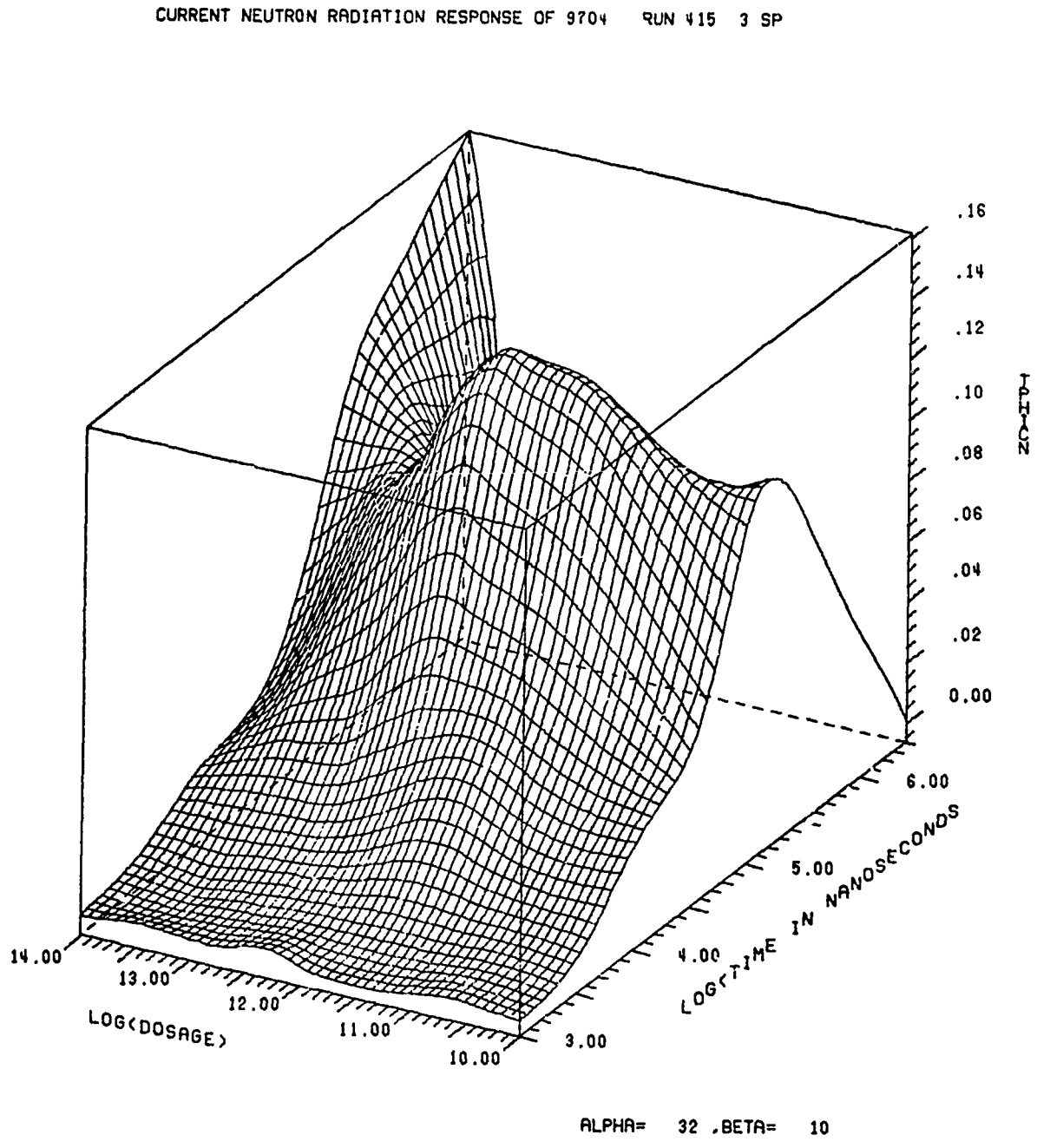


Figure 36b. Front View of Current Neutron Radiation Response of 9704, After Three Smoothing Passes

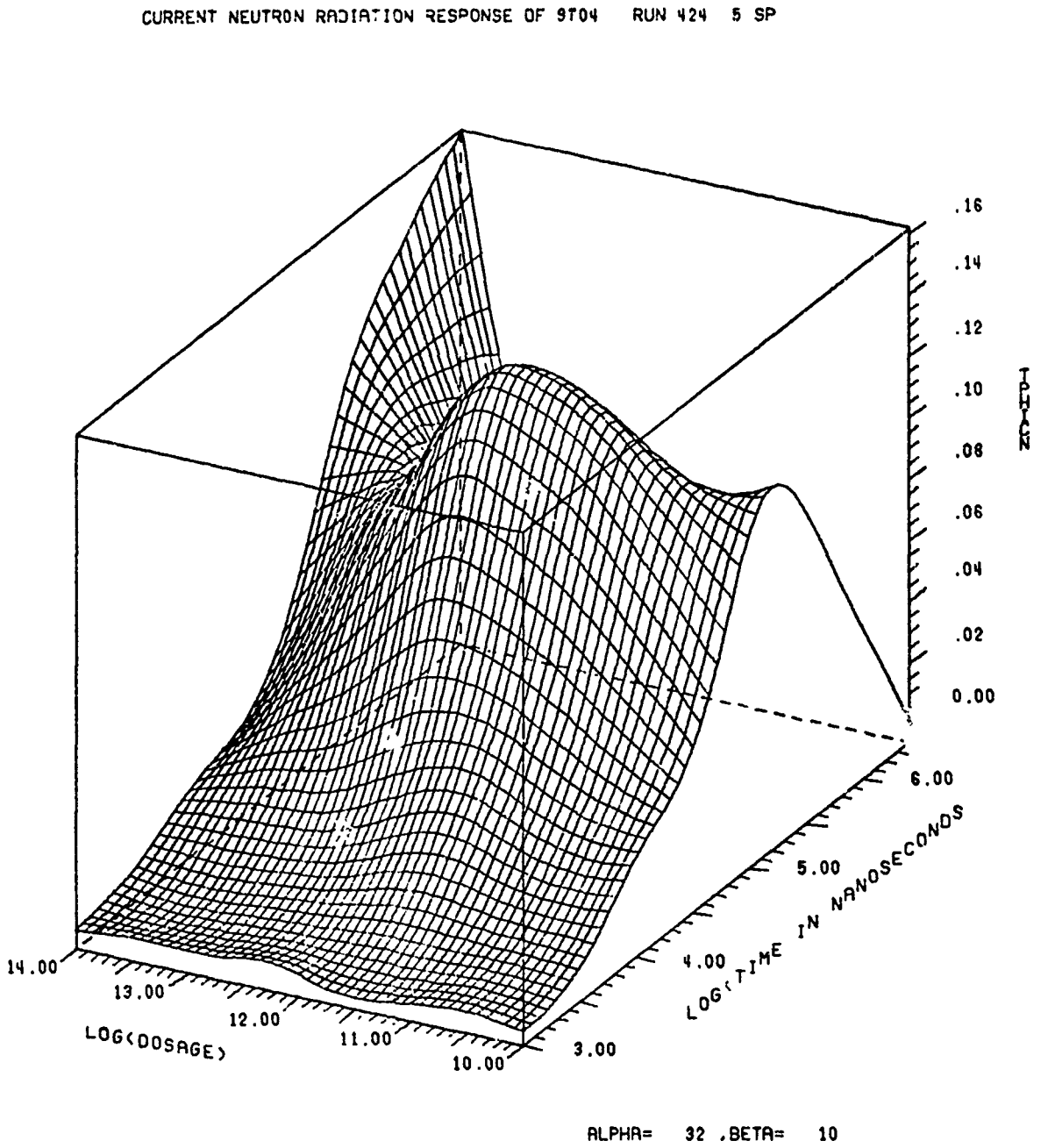


Figure 36c. Front View of Current Neutron Radiation Response of 9704, After Five Smoothing Passes

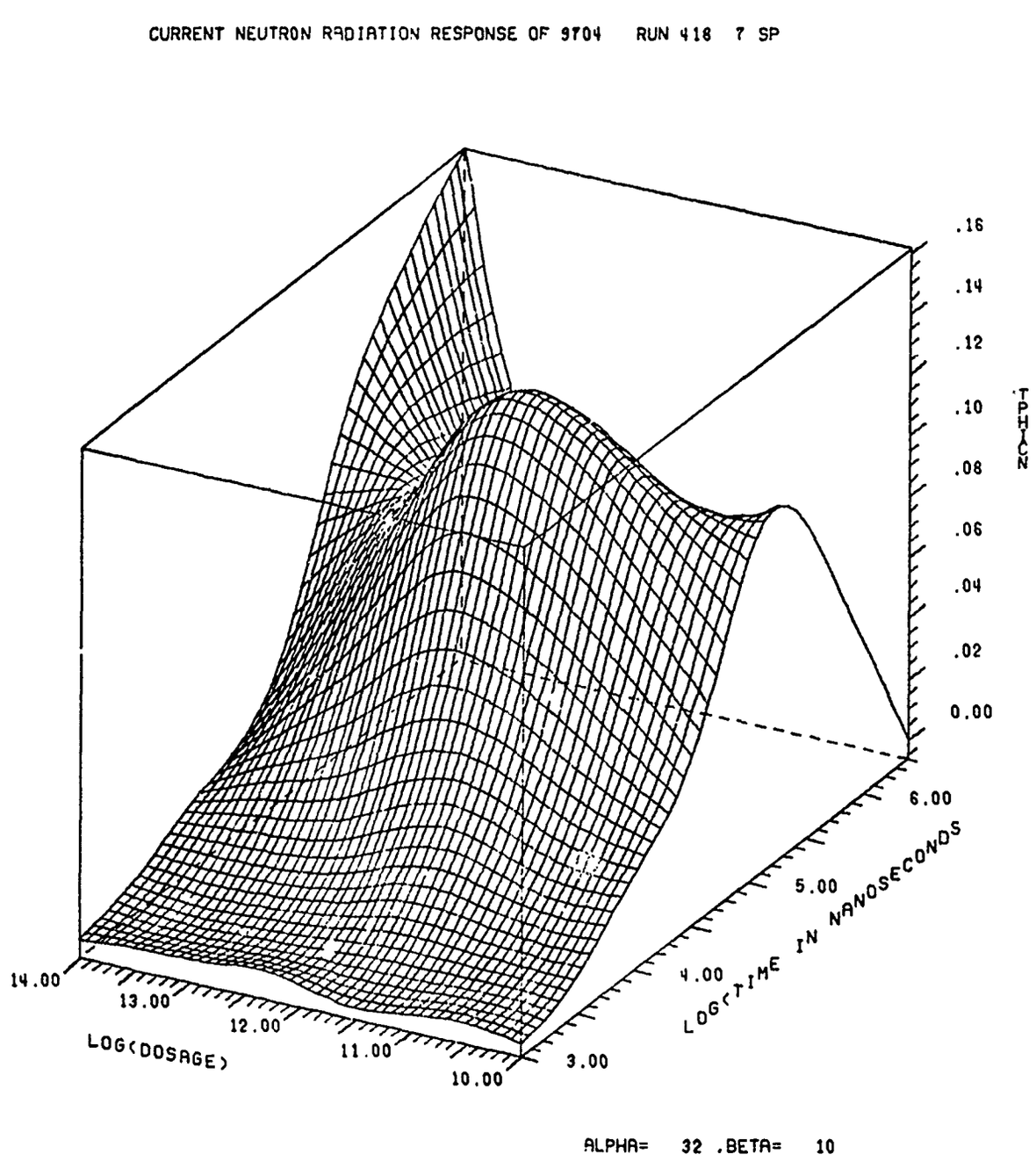


Figure 36d. Front View of Current Neutron Radiation Response of 9704, After Seven Smoothing Passes

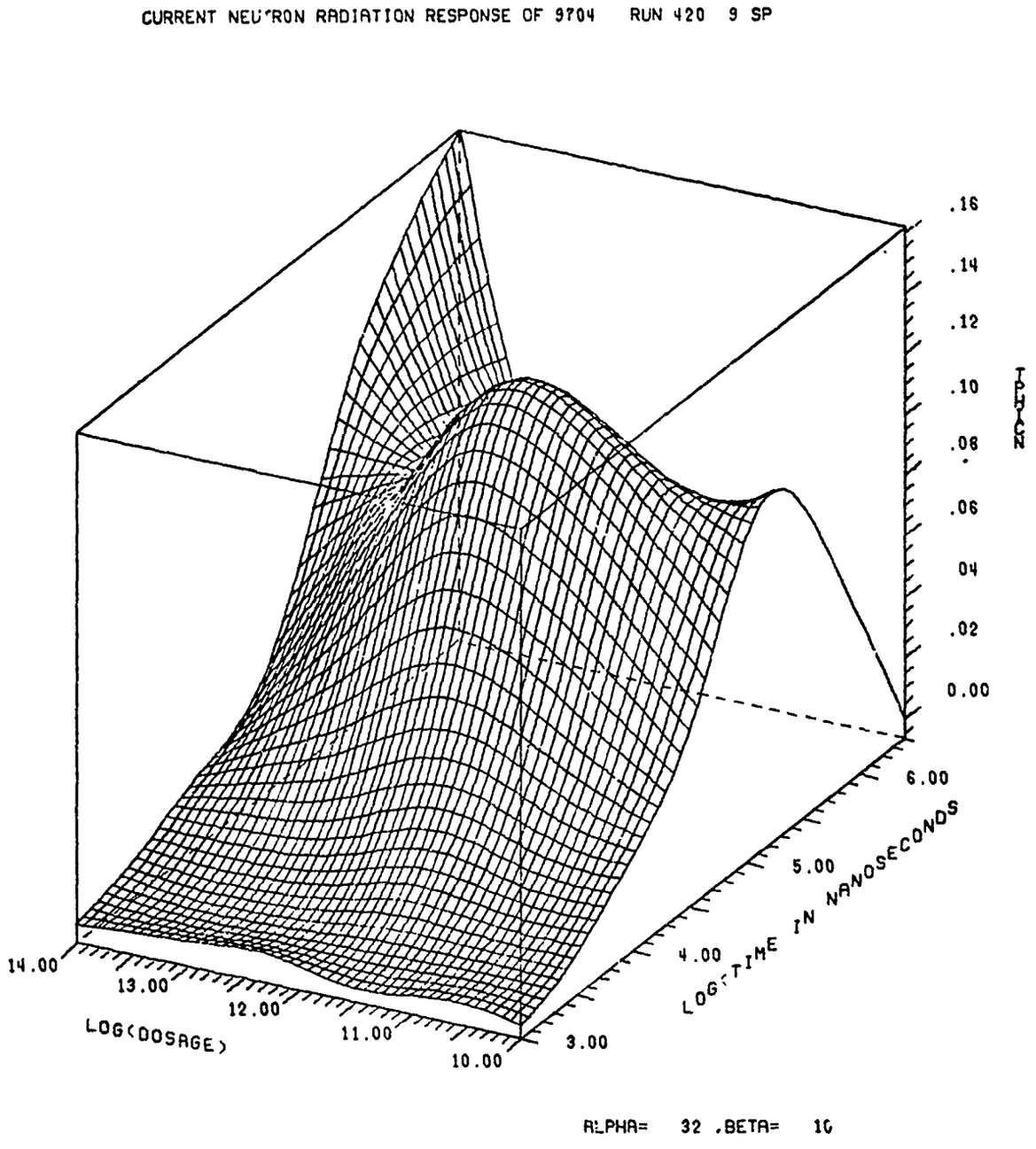


Figure 36e. Front View of Current Neutron Radiation Response of 9704, After Nine Smoothing Passes

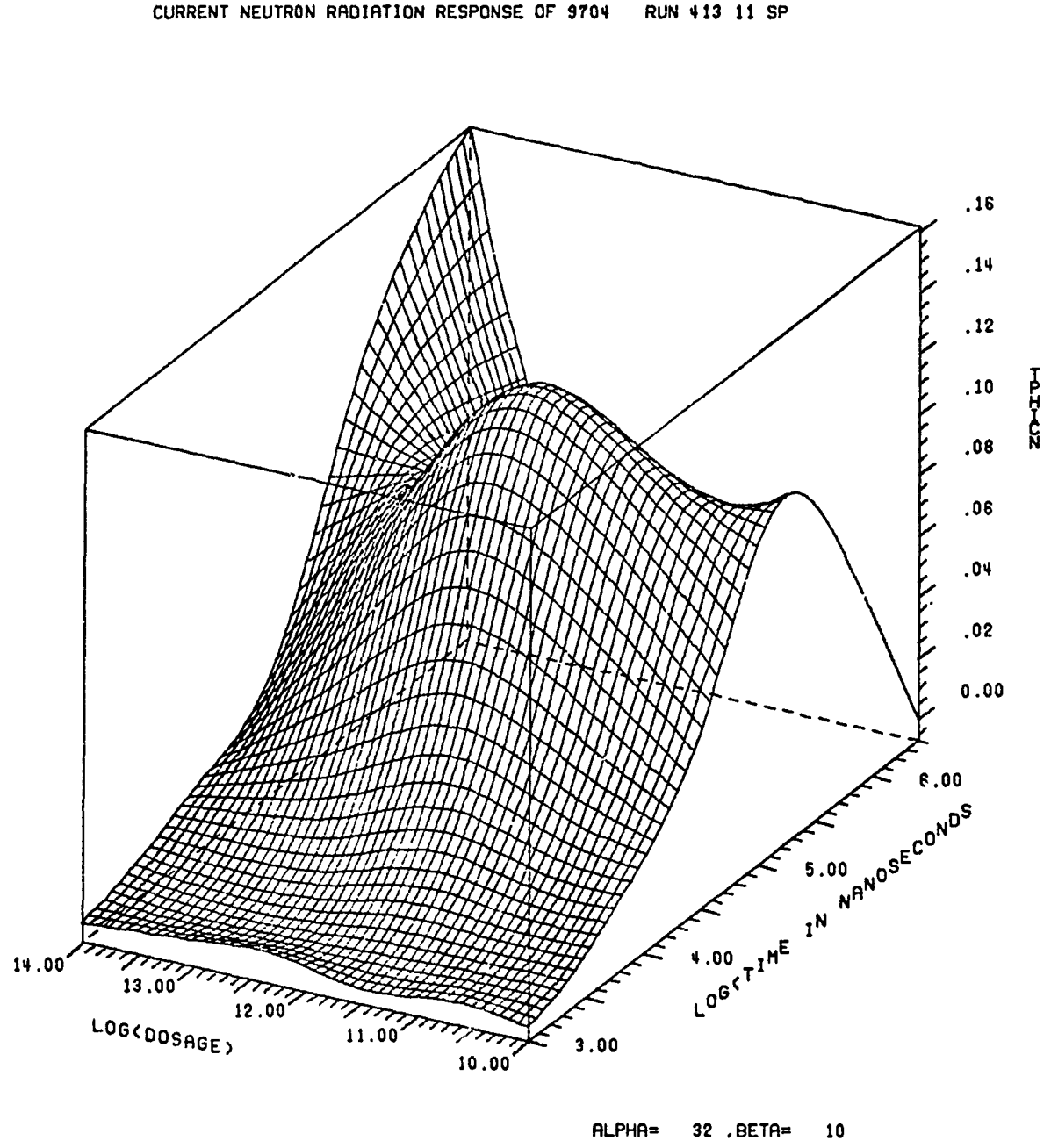


Figure 36f. Front View of Current Neutron Radiation Response of 9704, After Eleven Smoothing Passes

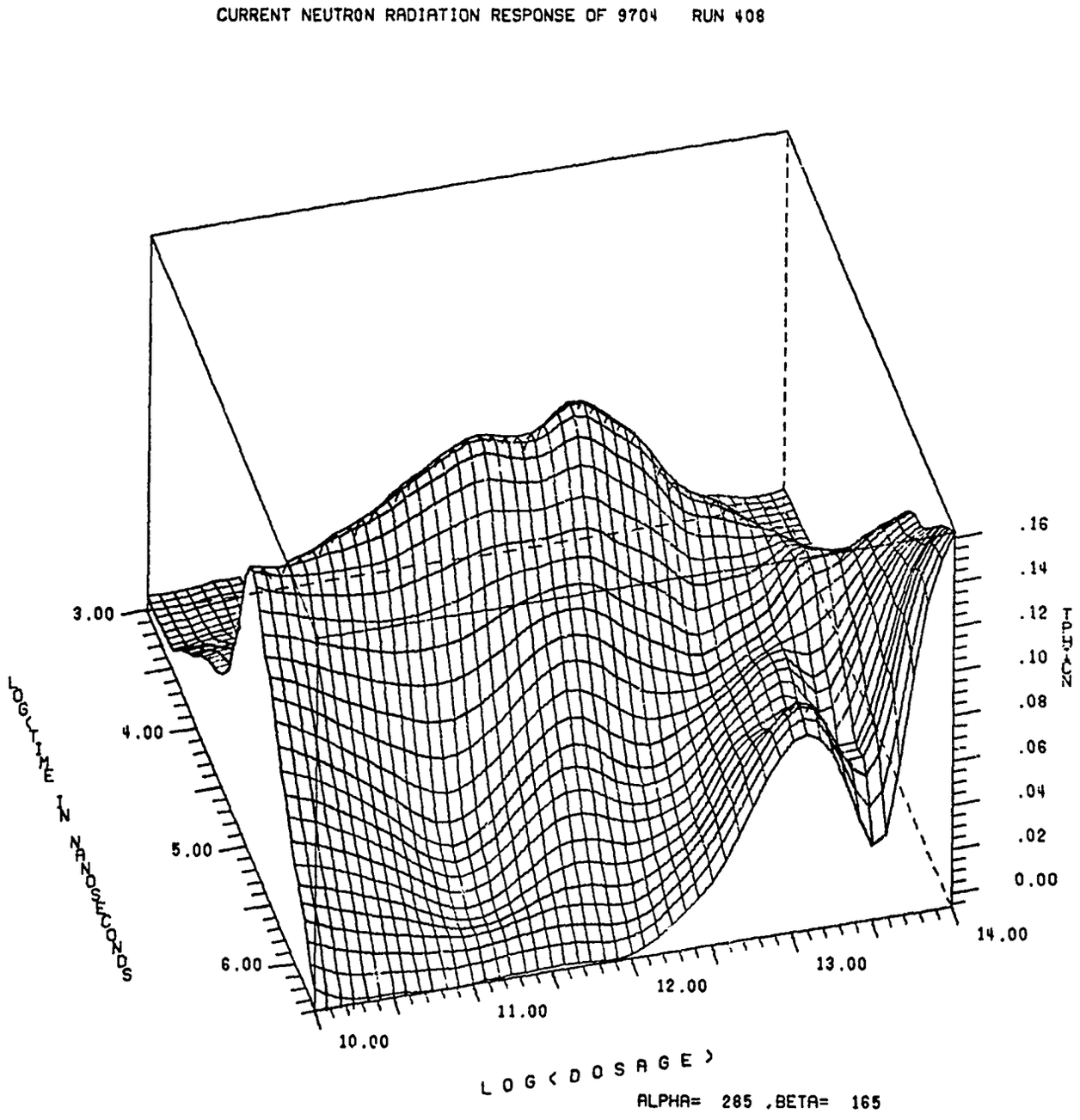


Figure 37a. Rear View of Current Neutron Radiation Response of 9704, After One Smoothing Pass

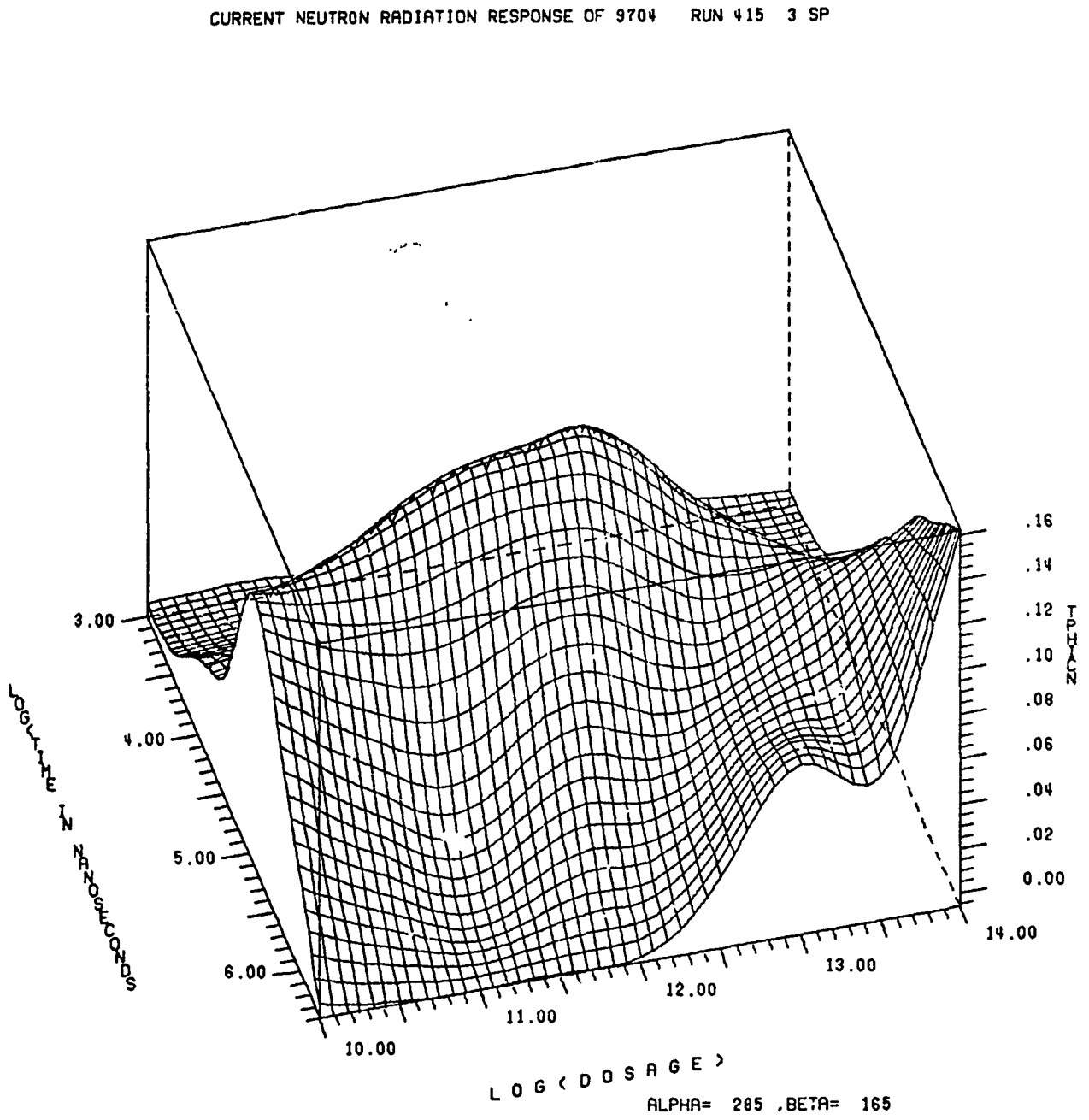


Figure 37b. Rear View of Current Neutron Radiation Response of 9704, After Three Smoothing Passes

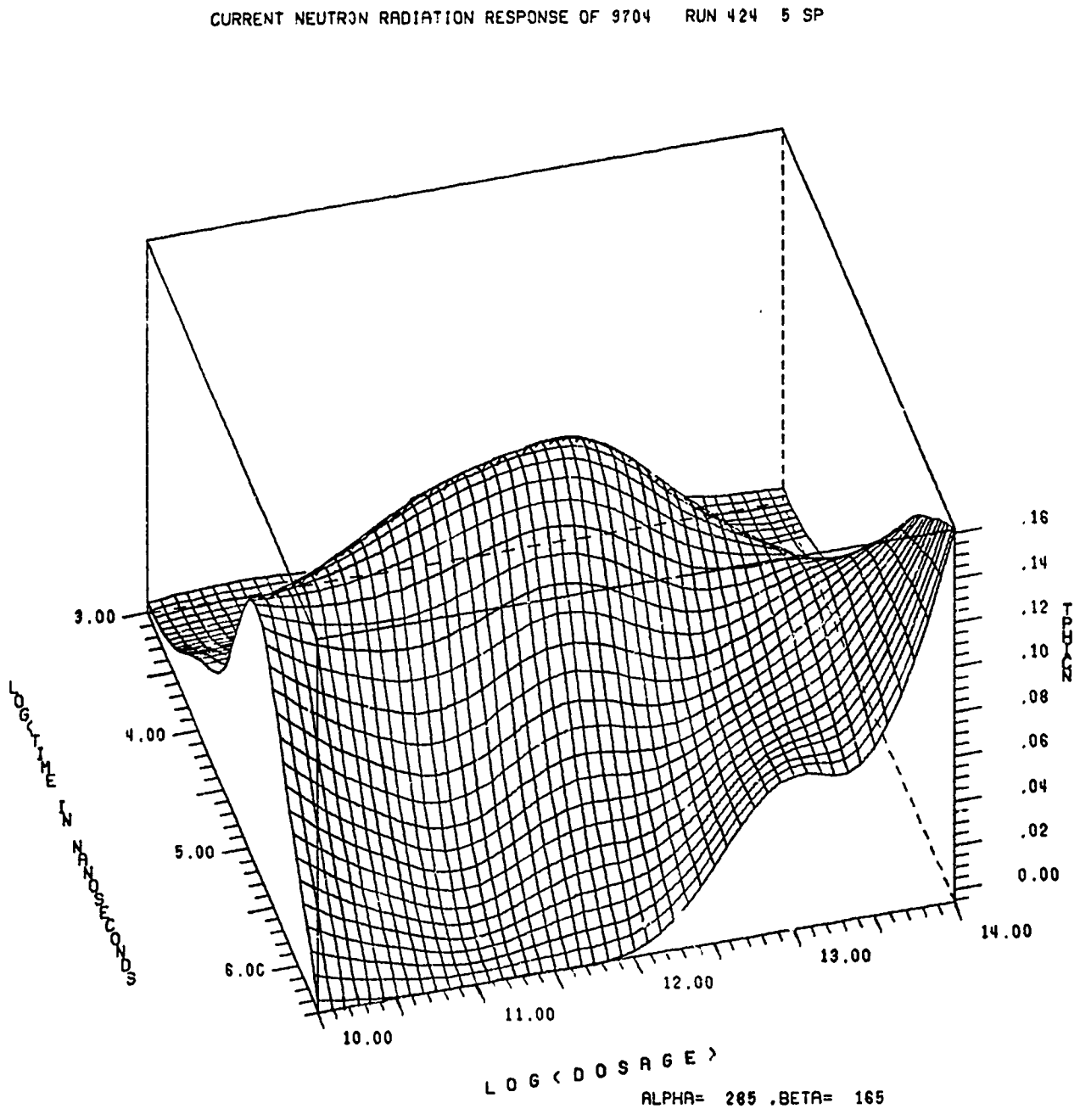


Figure 37c. Rear View of Current Neutron Radiation Response of 9704. After Five Smoothing Passes

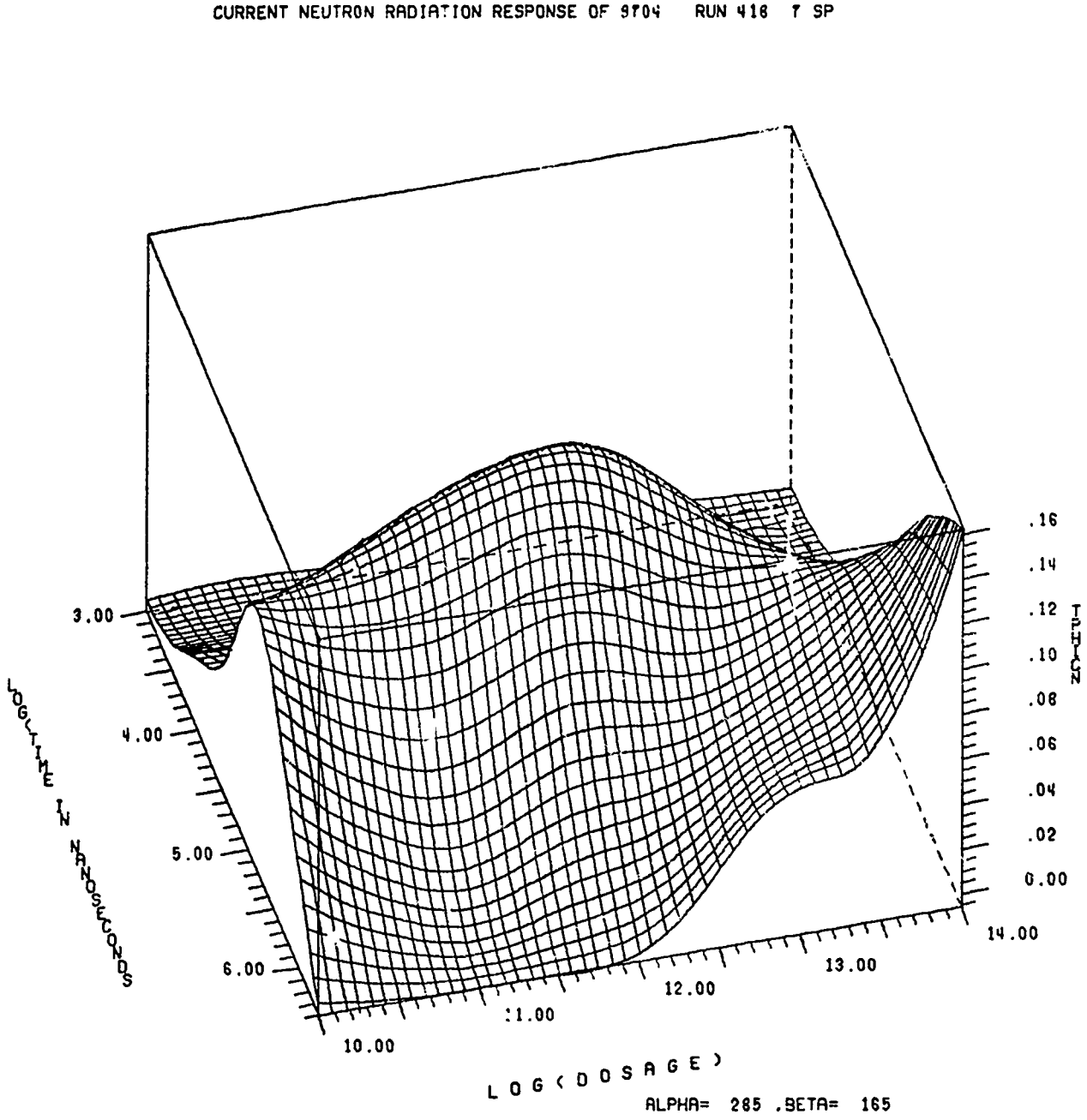


Figure 37d. Rear View of Current Neutron Radiation Response of 9704, After Seven Smoothing Passes

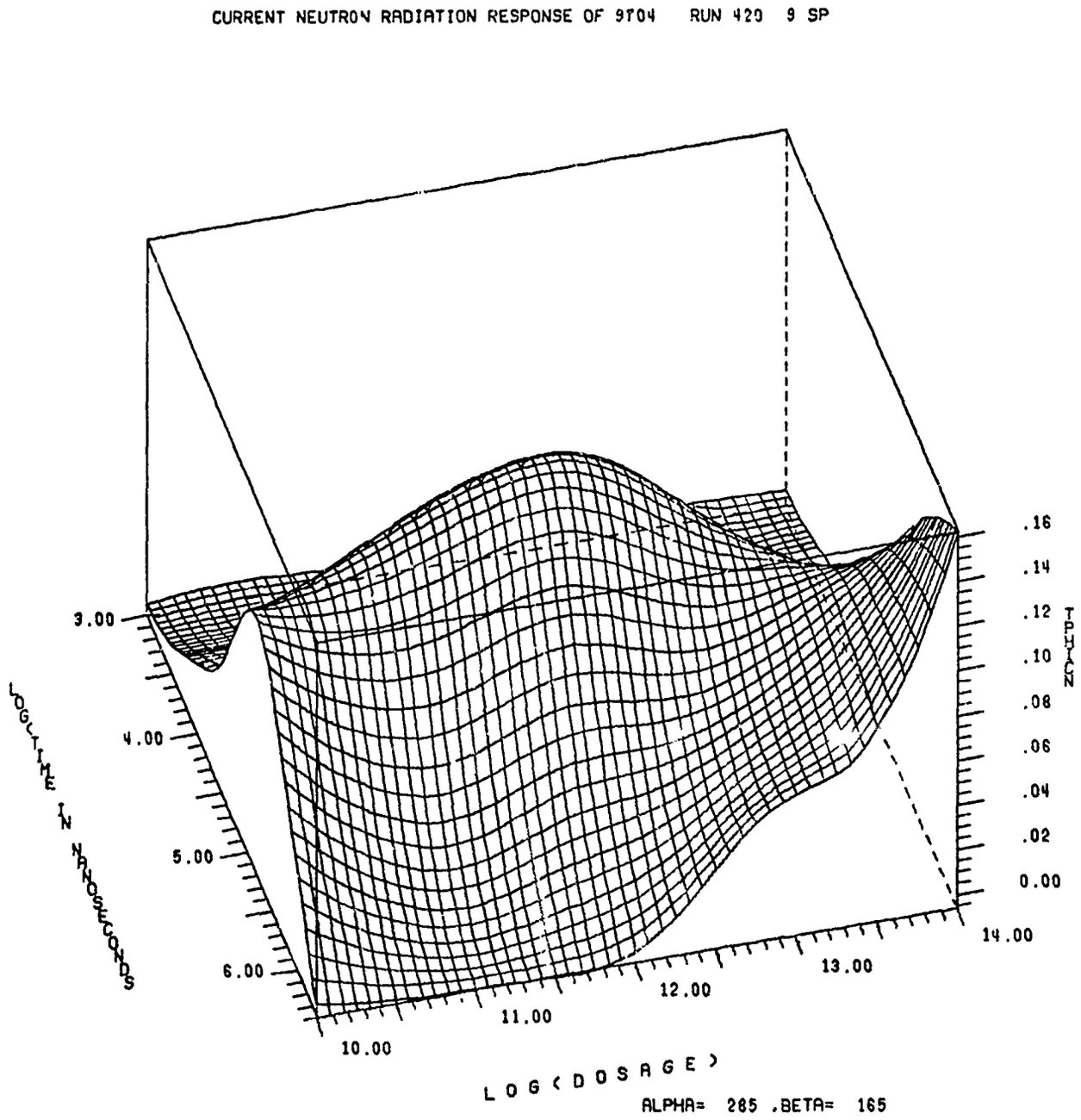


Figure 37e. Rear View of Current Neutron Radiation Response of 9704, After Nine Smoothing Passes

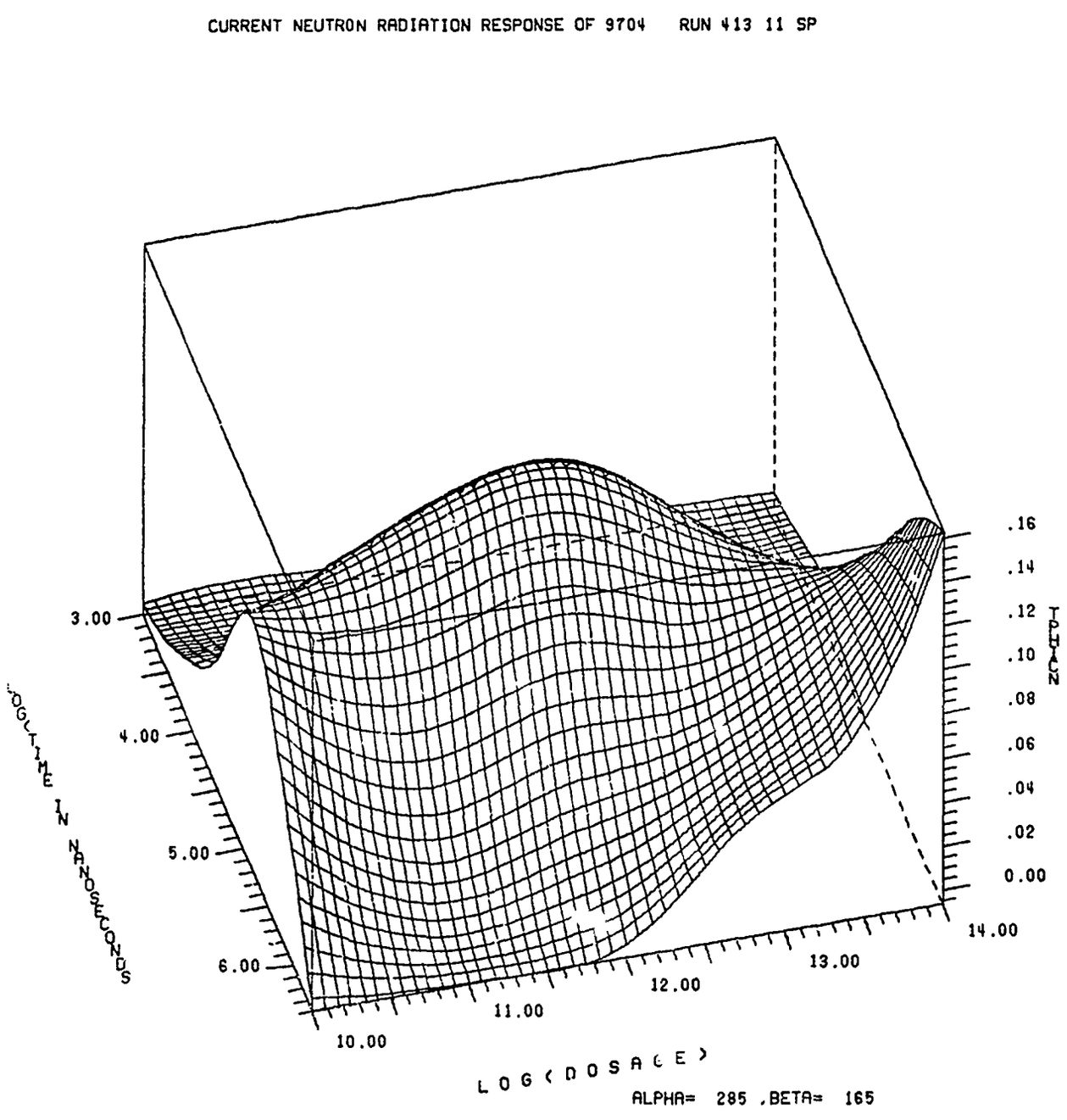


Figure 37f. Rear View of Current Neutron Radiation Response of 9704, After Eleven Smoothing Passes

quantitative criteria could probably be developed based on the amount of relative shifting that takes place on successive passes. Thus when the basic structure is reached, the relative shifts from the last pass presumably drop rapidly.

The prime conclusion however from the above example is that an appropriately applied combination of adding and deleting certain data points or strings, followed by astute choice of linear interpolation packing of the data plane, together with judicious application of smoothing and wild-pointing, can yield satisfactory computer representations of the basic experimental data without the necessity of first making a hand perspective drawing. However judgement is still required during the machine processing steps, particularly when treating the results of variability amongst different devices relating to threshold class of responses.

c. Gate Flash X-ray Response Surfaces

The first fitting of the voltage radiation transfer function of the 9704 NAND gate yielded the plot shown in Figure 38. While an initial impression might be that the surface doesn't tell much, on reconsideration it clearly shows the presence of a threshold type of radiation sensitivity, just as the neutron voltage response surface did. It leads to speculation that perhaps the neutron-gamma ratio of the fission burst is not so high that some of the observed neutron results are likely due to the incident gammas. Taking an n-γ ratio of 5×10^{8}, then a neutron dose of 5×10^{13} gives a gamma dose of 10^{5} rad. The time scaling of the FXR is about 5000 times less than that of the SPR, hence, the dose rate or $\dot{\gamma}$ is the order of 5×10^{8} rad/sec. The radiation sensitivity threshold for the 9704 gate at the FXR was about 3×10^{10} for a transition in the output voltage logic state level. However, photocurrent contribution were clearly evident at dose levels two or three orders of magnitude less in the current response surfaces.

Additional projection plots of the voltage response function for FXR exposure are shown in Figure 39 a and b. The vertical scale problem evident in Figure 38 was corrected yielding a larger range on the z axis.

Smoothing was applied to this surface with the results of run 502 shown in Figure 39 c, d, e, and f. It is apparent by inspection of the corner of the surface at maximum dose and minimum time, that the smoothing is driving the corner data points downward in an erroneous manner. This is readily observed by comparing Figure 39 b with Figure 39 d. The smoothing does reduce some of the bumps elsewhere

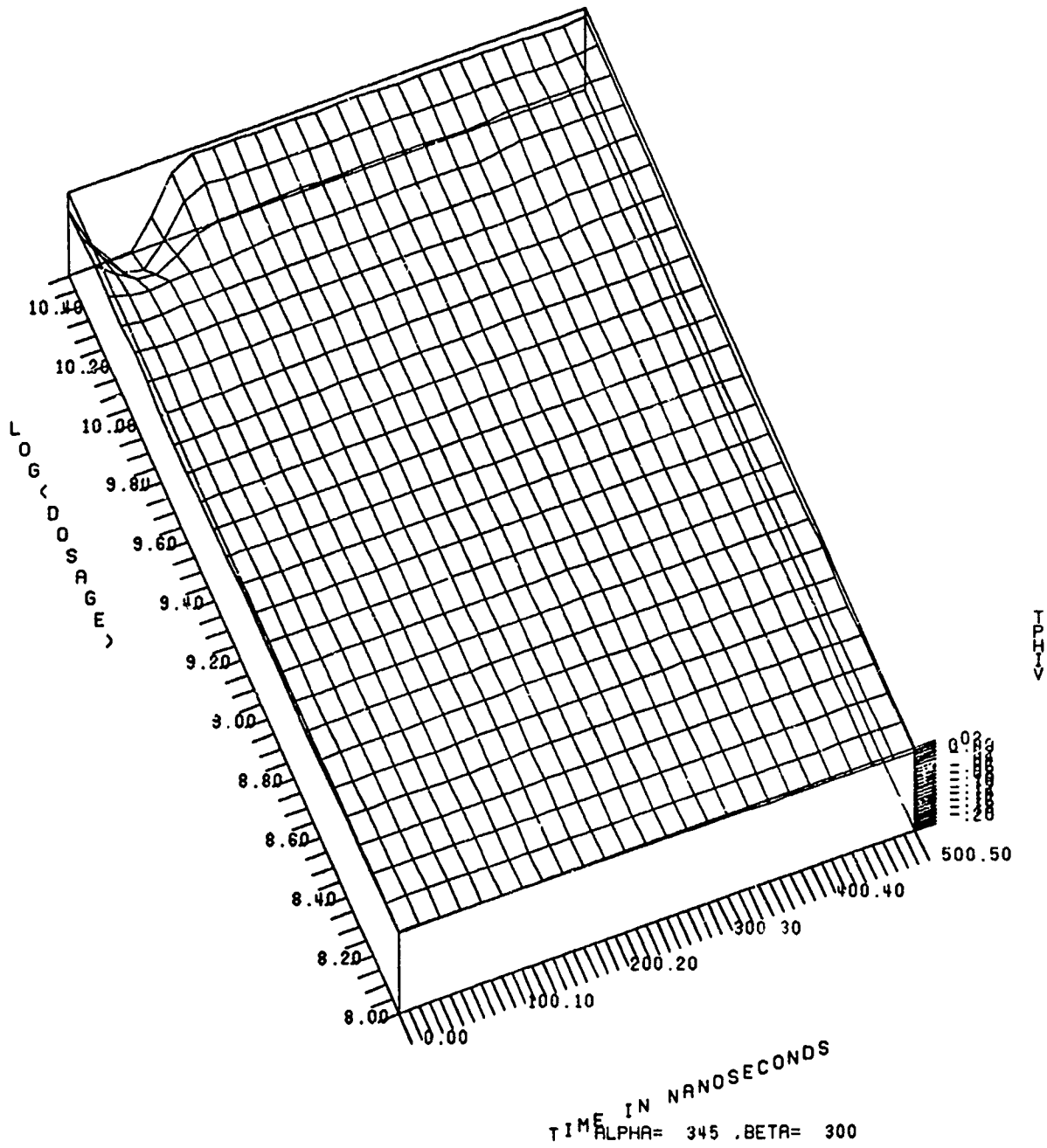

FXR VOLTAGE RADIATION TRANSFER FUNCTION OF 9704
LOG(DOSAGE)
10.40
10.20
10.00
9.80
9.60
9.40
9.20
9.00
8.80
8.60
8.40
8.20
8.00
0.00
100.10
200.20
300 30
400.40
500.50
TIME IN NANOSECONDS
ALPHA= 345 .BETA= 300
IPHIV

Figure 38.

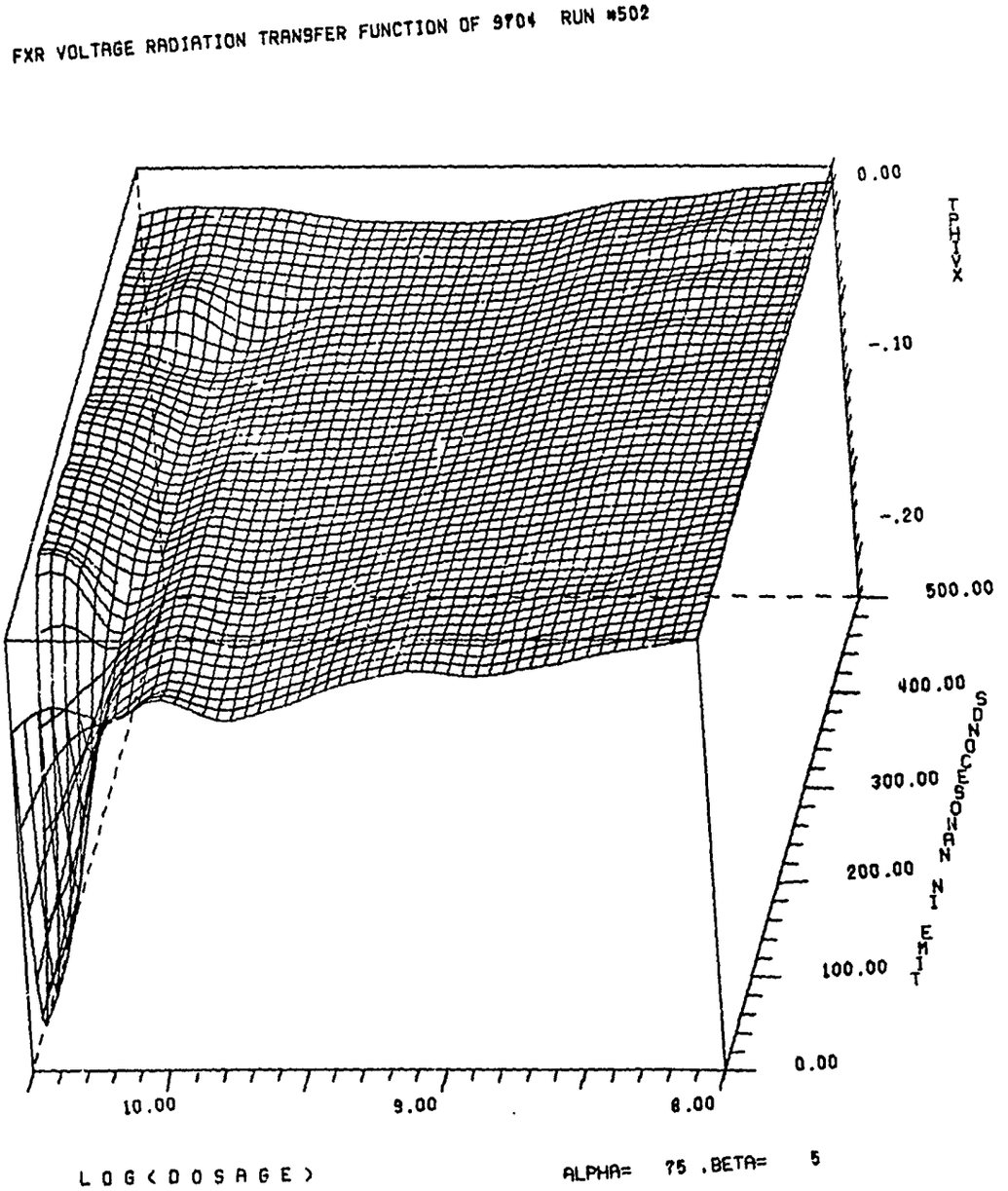


Figure 39a. Front View of FXR Voltage Radiation Transfer Function of 9704 Gate, Note Existence of a Threshold

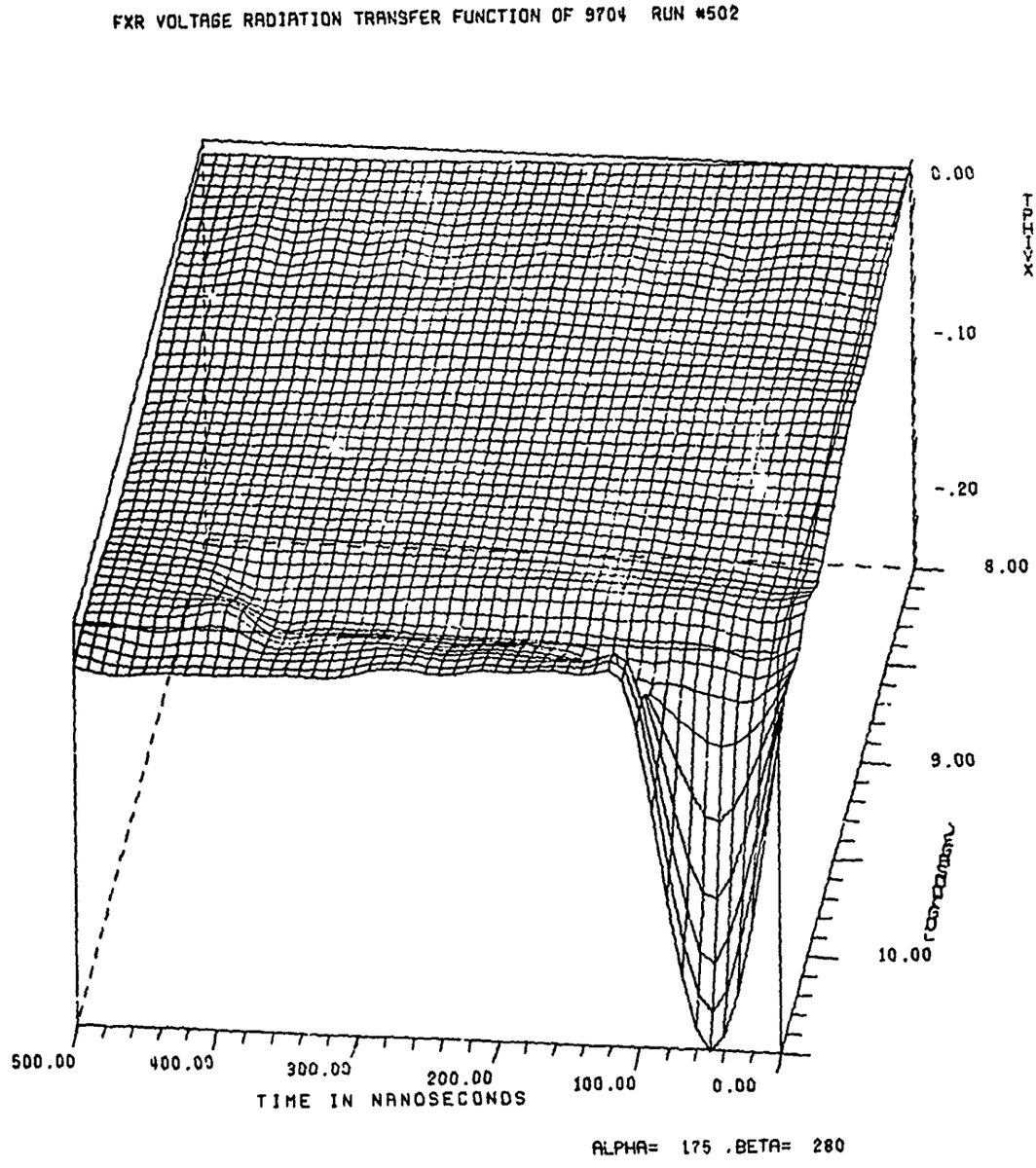


Figure 39b. Side View of FXR Voltage Radiation Transfer Function of 9704 Gate

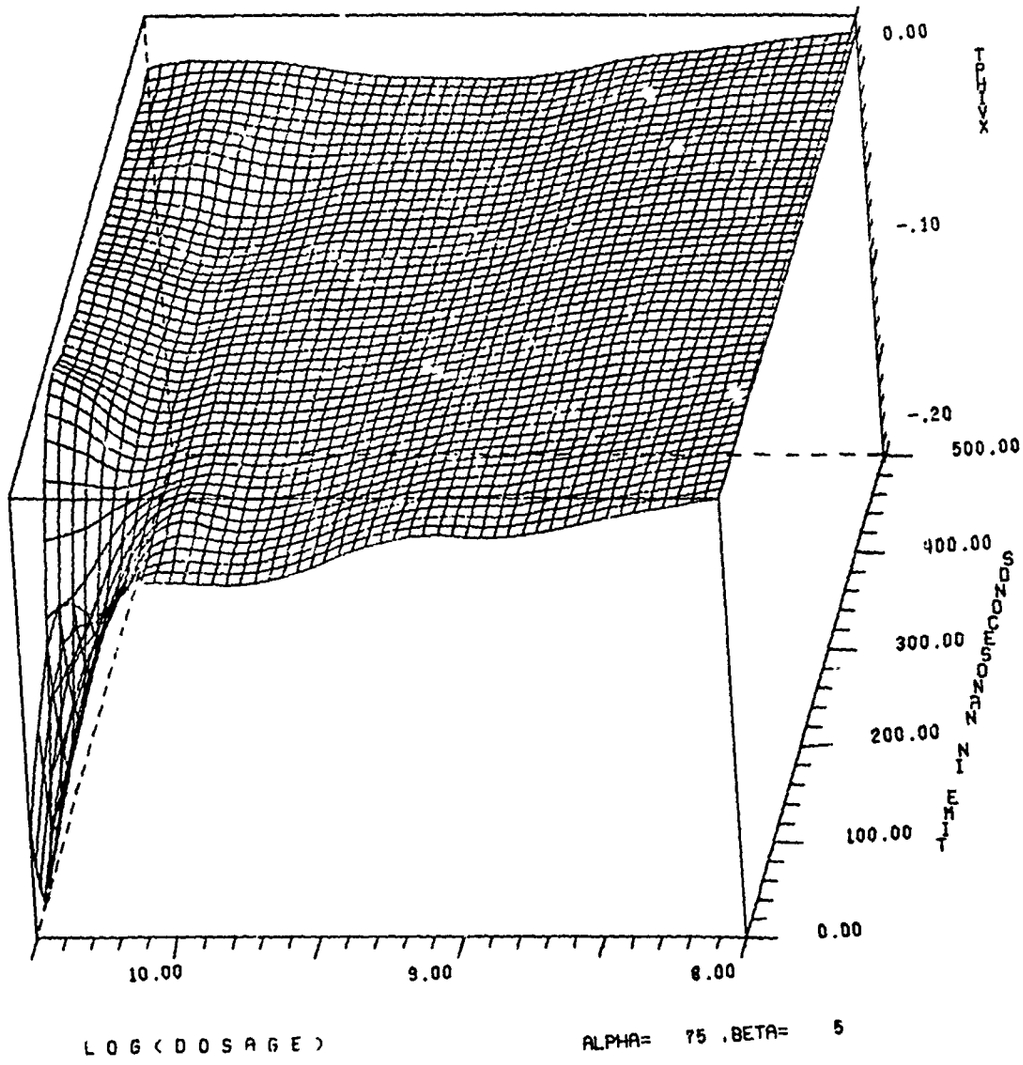


Figure 39c. Front View of FXR Voltage Radiation Transfer Function of 9704 After One Smoothing Pass

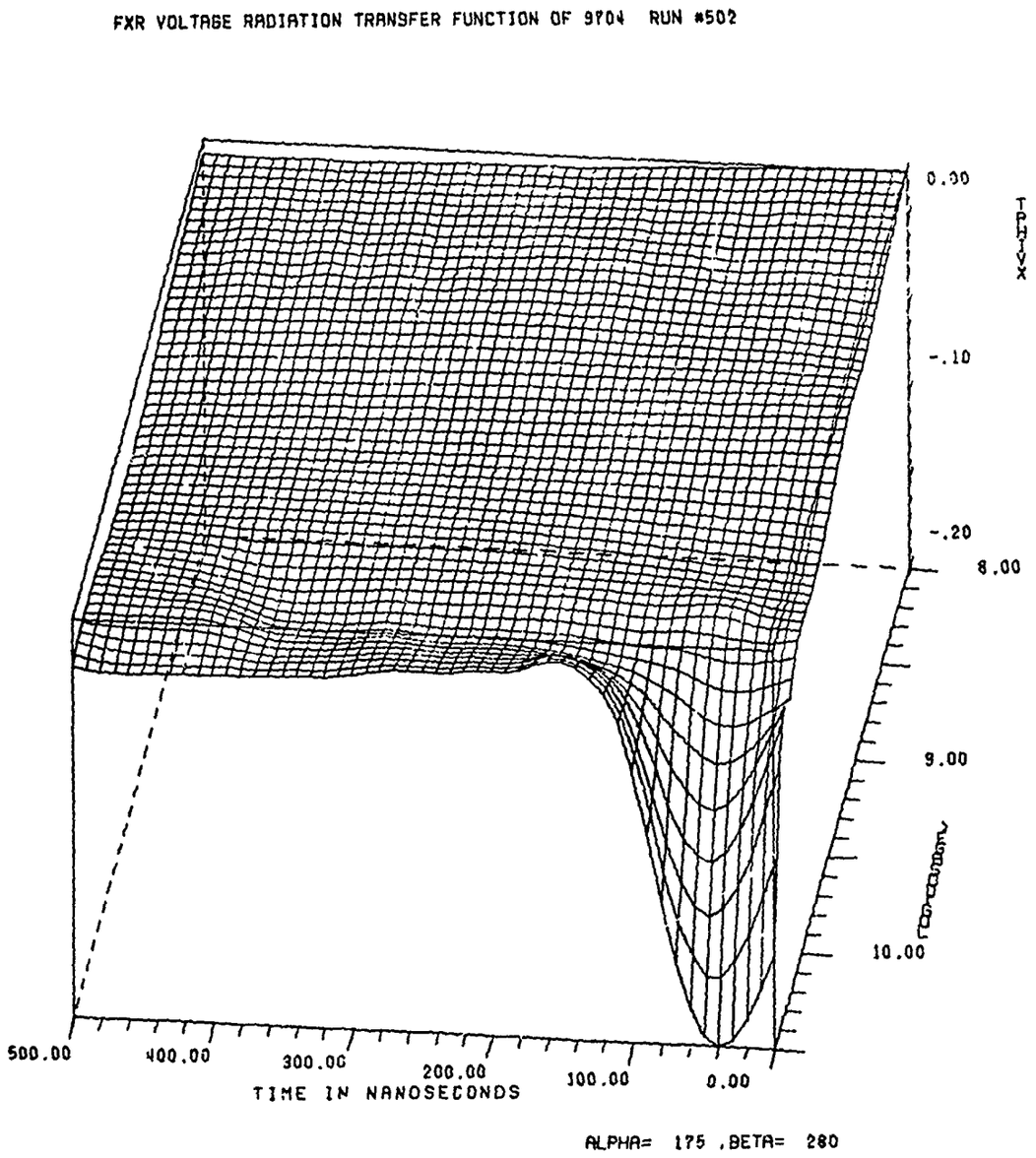


Figure 39d. Side View of FXR Voltage Radiation Transfer Function of 9704 After One Smoothing Pass

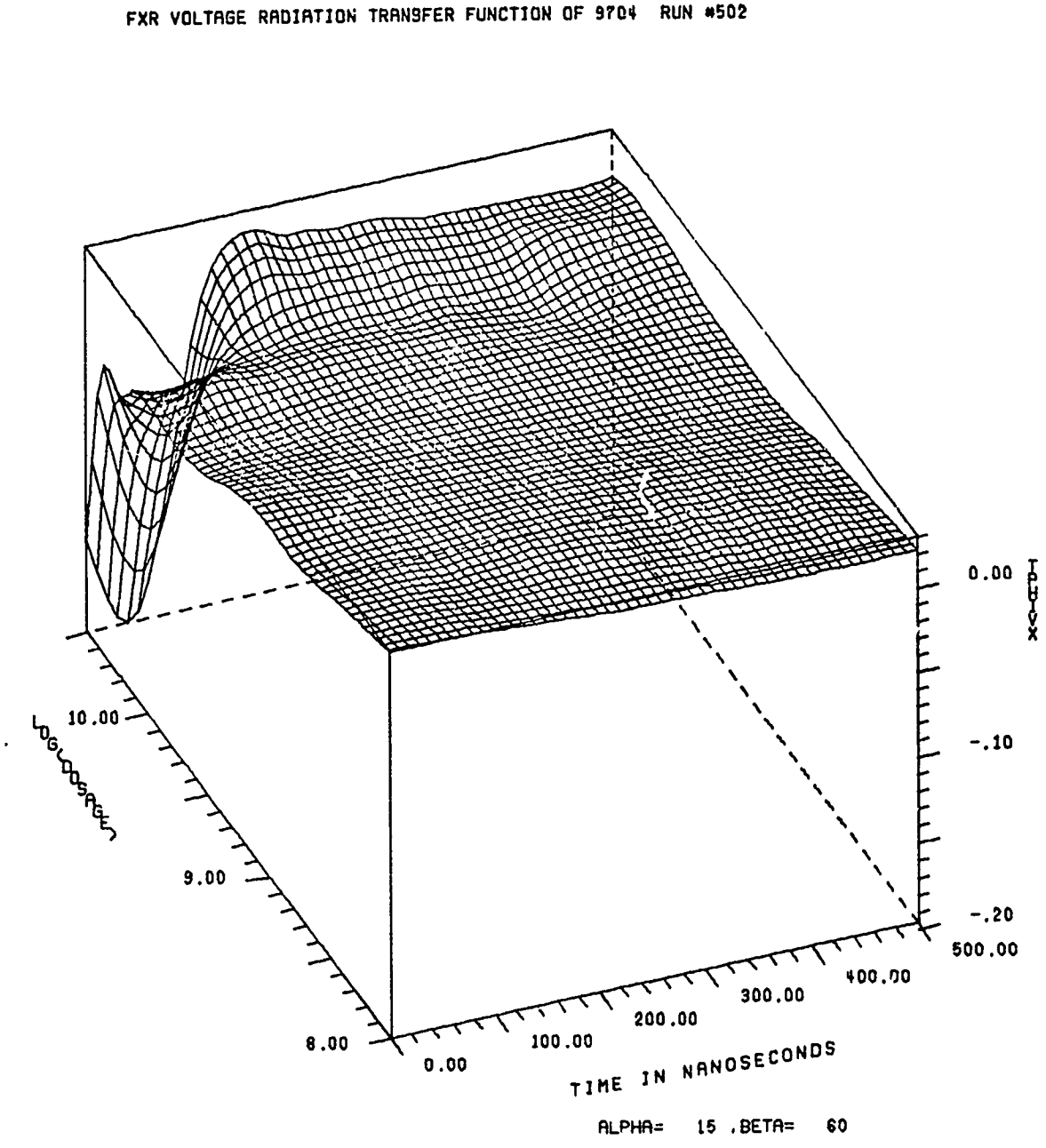


Figure 39e. Oblique View of FXR Voltage Radiation Transfer Function of 9704 After One Smoothing Pass

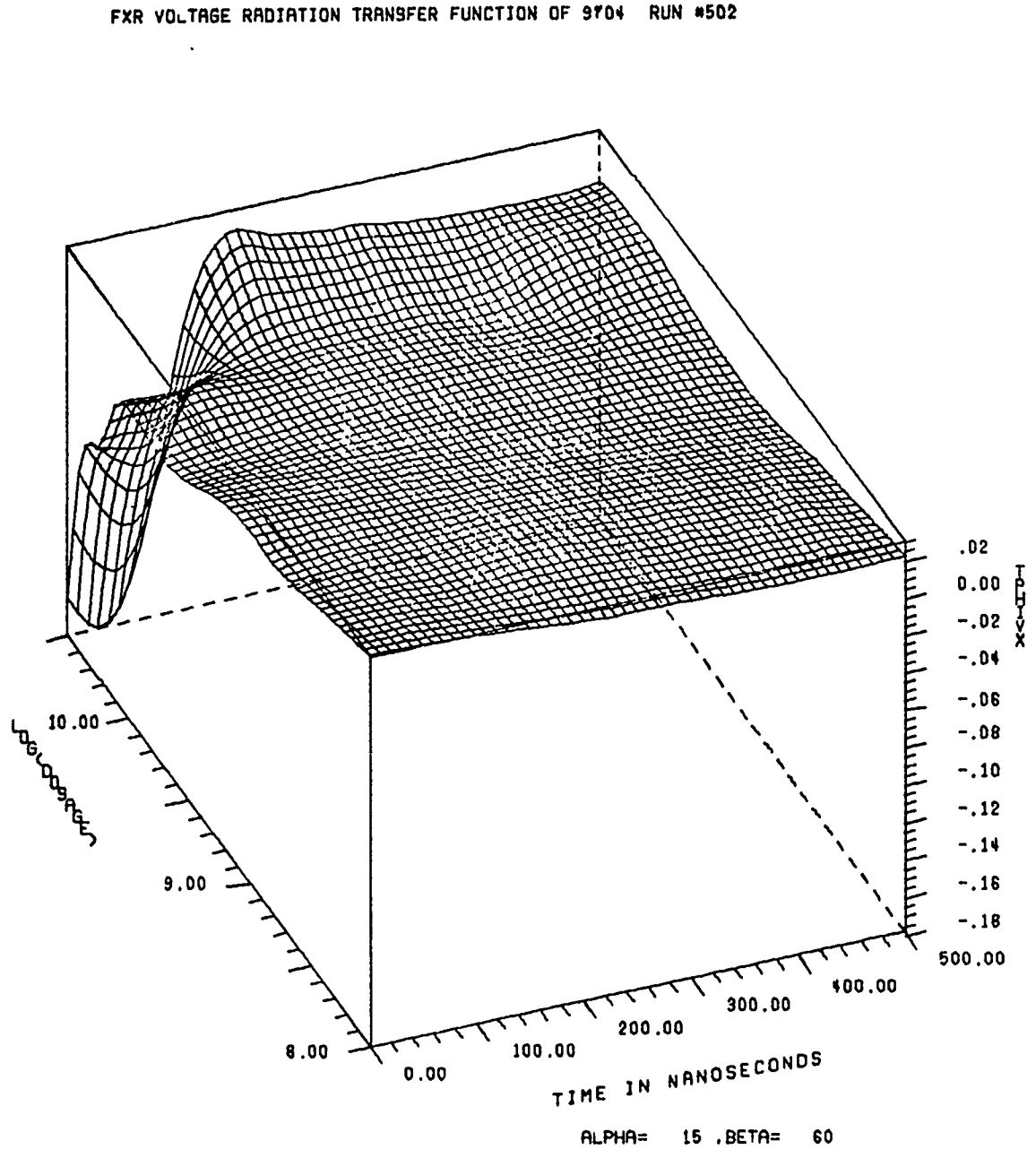


Figure 39f. Oblique View of FXR Voltage Radiation Transfer Function of 9704 After Two Smoothing Passes

in a way which is acceptable. However, th. need for anchoring of some data points to hold them fixed with respect to the smoothing operations is clearly mandatory in this case. The present sequence of calls from FITIT to NICER, SMOOTH, and DUZ2 do not allow this option, and should be modified in the future.

The FXR-induced current output of the gate, as loaded with the four inputs of the following gate in the dual NAND package, is shown in Figure 40. The oscillations present in the output are very evident at low dose levels. The oscillation frequency is approximately 10 MHz. The behavior of the surface at higher dose levels shows portions of this ringing frequency also. The rather disturbed appearance at high dose levels is the result of fitting a number of data strings from different shots and devices, with not only their own inconsistencies, but also the error components arising from trigger differences, and those of the hand digitization of the Polaroid photographs. The amplitude of the signal from the Tektronix CT-2 current transformers is in the millivolt range so that the maximum gain of the Tektronix 7704 oscilloscope was required in order to observe the traces. Noise and drift of the signal were consequently severe.

The FXR response surfaces for the gate as presented above were plotted vs. time itself as the independent variable along the x axis, rather than the logarithm of time as was the case with the neutron response surfaces and the 741 response surfaces. This posed some problems in the later analysis program SAP, so an attempt was made to fit the gate FXR surfaces similarly with a log (time) representation along the x axis. The results for the current radiation surface from run 498 appear in Figure 41. The effect of the linear to logarithmic time transformation is to devote about one-third of the fitting function to the time interval between 1 and 10 ns after trigger, during which interval very little happens, and to essentially eliminate any of the detail in the ringing after about 70 ns. The resulting fit is certainly not satisfactory. Thus, it is evident that a log(time) axis will be satisfactory only if the fundamental structure of the surface decreases sufficiently rapidly with time. It would appear that a circuit or system whose impulse response function continues with rapid variations for long times, such as an oscillator, should not be fit with a log(time) representation.

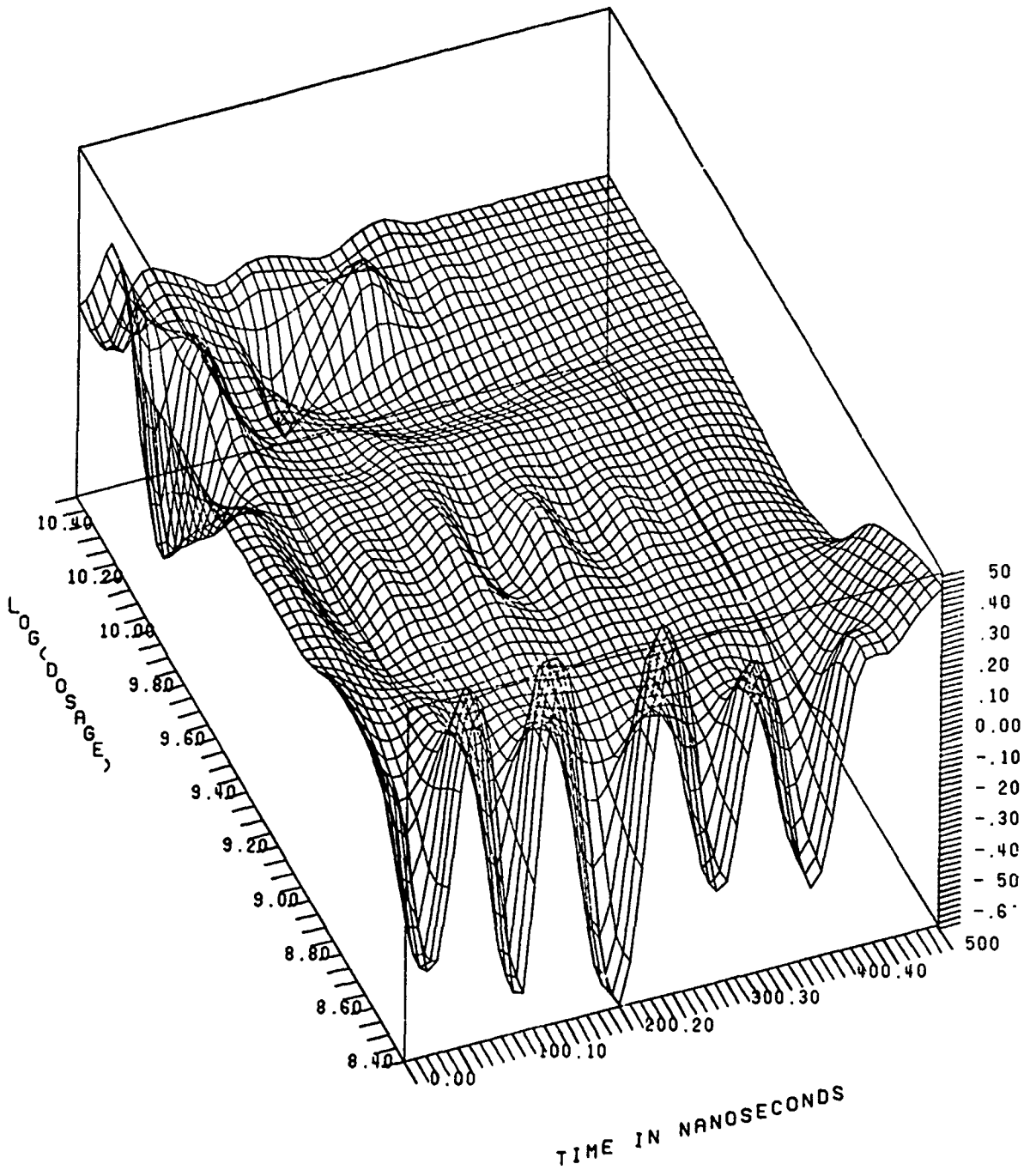


Figure 40. Oblique View of FXR Current Radiation Transfer Function of 9704 with Linear Representation along Time Axis

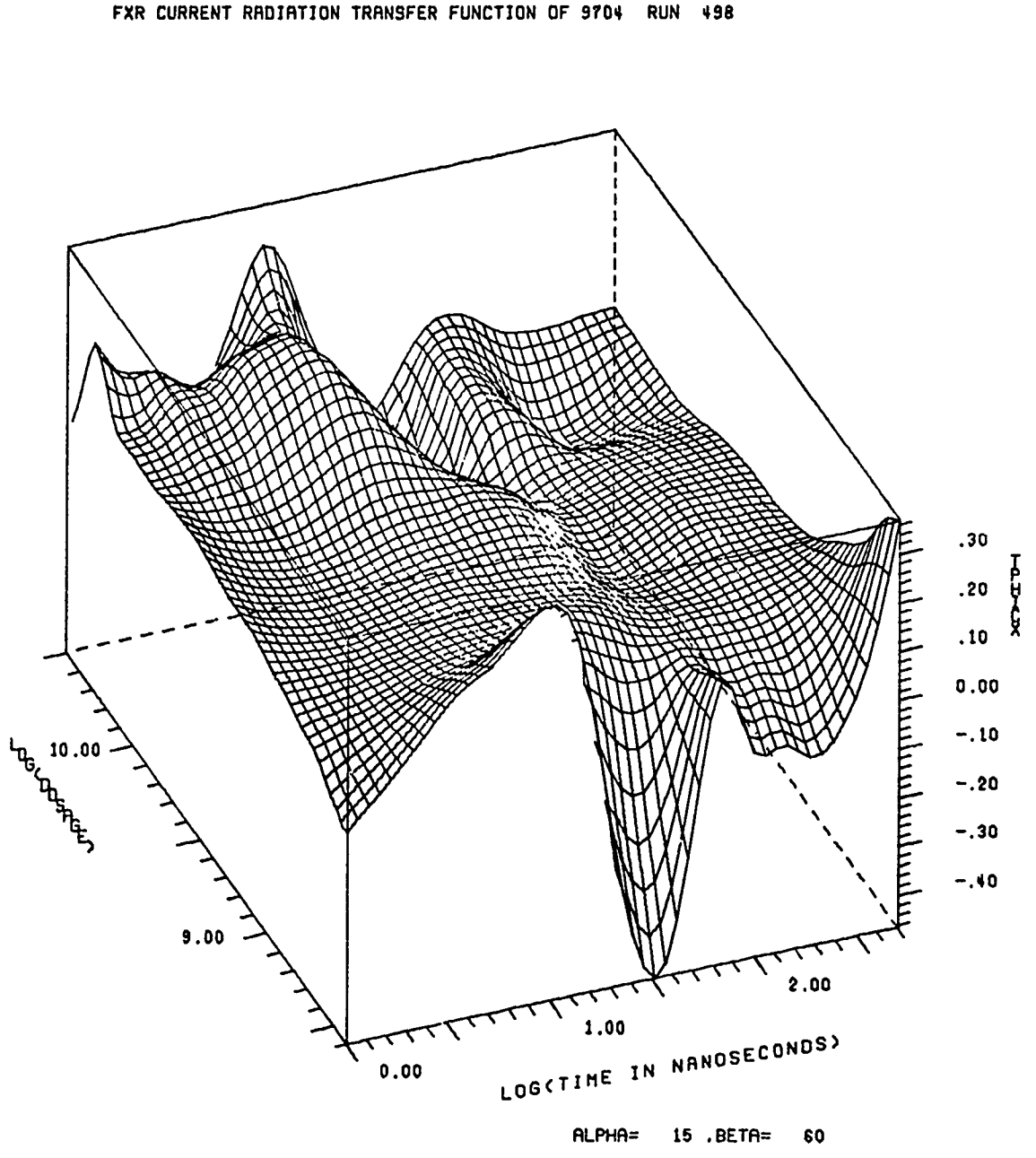


Figure 41. Oblique View of FXR Current Radiation Transfer Function of 9704 with Logarithmic Representation along Time Axis

SECTION V

SAP COMPUTER PROGRAM

1. GENERAL ORGANIZATION

The overall logic flow in the computer program SAP is shown in the flowchart presented in Figure 42. The first seven steps are essentially initialization procedures which bring in the surface ZCOEF files from drum storage; read data cards describing the circuit configuration, radiation forcing function, and voltage waveform; and then the control and title cards for the plots.

The execution of the computational strategy discussed in detail in Section II is initiated at step 8 which is the DO loop driving the time stepping and runs to step 16. The time stepping is a simple constant increment determined by the data card stream. The time base can be either linear or logarithmic. The mode of the time base affects the convolution process, as will be discussed below. Next, the subroutines RADGEN and VOLTIM are called to obtain the radiation and voltage forcing functions at a given time step.

At step 10 in the flow chart, the adjusted input variable is obtained by extrapolating the value at the last time step by the ratio of the new and old fixed input variables. If the input element is close to linear, the new iterate can be reasonably close to the correct value. Then the iteration routine DRIVER is called to initiate the Newton-Raphson iteration cycle. The iterate is returned to MAIN. Step 12 starts a DO loop which runs down through step 14, and acts to propagate the adjusted and fixed input variables through the chain of blocks to the output node.

As the above DO loop drives along the chain of blocks, successive calls to FE and FI are made to obtain the voltage and current transfer functions of the blocks. If the block element is simple, such that an equation suffices for the transfer function, FE or FI will return that result to MAIN. If surface look-up and convolution are required, then FE and FI will drive into CONVOL, TSURF, and SURFC. CONVOL basically handles the convolving of past time steps dynamical responses, and the interrogation of the surface routines for evaluation of the contribution of the current time steps present iterate to the output. Note that the convolution operation is needed only once for each time step, and that the

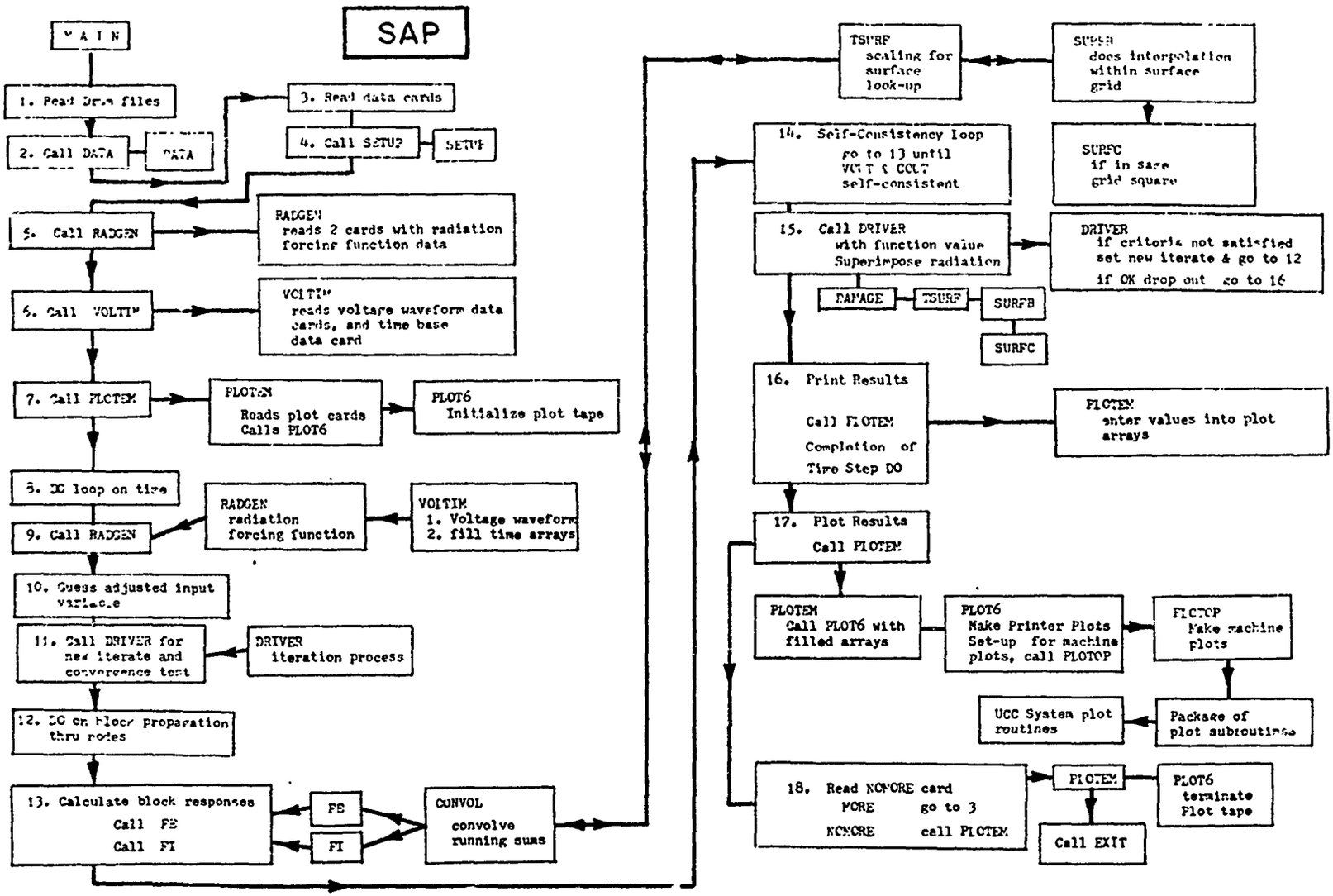


Figure 42. S A P Flowchart

evaluation of the present iterate's contribution involves only one surface look-up rather than a look-up for each term in the convolution sum. Thus, the execution speed of convolutional dynamical evaluations can be rather high. The routine TSURF handles scaling of function values for the surfaces, and takes appropriate actions if the input variables are out of the range of the surface. SURFB and SURFC use the ZCOEF arrays read in by MAIN to perform surface evaluations by interpolating within the grid squares. The execution time is approximately 2 ms per surface look-up.

The self-consistency loop at step 14 essentially attempts to compensate for a computational delay inherent in the calculation if the voltage transfer function depends on the output current, at a given time step and a given iterate. Since the voltage is calculated first through FE, the first result will be using the current from the last time step. The next statement in MAIN updates the current for the present iterate. The self-consistency loop then goes back and recalculates the voltage for the block with the new current and tests for self-consistency with the values of the last pass. When the voltages and currents agree within some desired value with those of the last pass, the self-consistency criteria are satisfied and control passes to the next step in the program.

At step 15 the routine DRIVER is called thereby providing it with the function value of the fixed output variable. DRIVER then tests for satisfaction of the convergence criteria, and either forms a new iterate and returns to step 12, or is satisfied and continues to step 16. At 16 the results for the time step are printed out, and PLOTEM is called to enter them into the plot arrays. This then completes one time step, and the program returns to the beginning of the DO at step 8.

After completion of the time step DO, at step 17, PLOTEM is again entered to initiate printer and machine plots through PLOT6, PLOTOP, the plot subroutine package, and the UCC machine plot routines. Finally, at step 18 a data card is read which returns to step 3 if it says MORE, or calls PLOTEM and PLOT6 to terminate the plot tape and then calls EXIT if the card says NOMORE.

2. PROGRAM MAIN

Since the overall logic of MAIN was described in the section above relating to the flow chart, here we shall just describe some of the details of the data card decks. The listing of MAIN is given in Figure 43. The surface ZCOEF decks are

```
      P ELT MAIN,1,720302, 47795     , 1

000001            C     PROGRAM MAIN
000002                  INCLUDE SAP,LIST
000003                  INCLUDE TIME,LIST
000004                  INCLUDE XYZ,LIST
000005                  COMMON / DEBUG / IDEBUG
000006                  LOGICAL IDEBUG
000007                  DIMENSION NIN(IX),NOUT(IX),LBLOCK(IX,IX),ISURF(NSURF),LTIME(2)
000008                 1,JPARAL(IX),FACTOR(IX),CNOUT(IX),VNOUT(IX),CNIN(IX),VNIN(IX)
000009                 2,LMEX(IX)
000010                  LOGICAL IRADX,IRADN,INITAL,ISYM,ISYML
000011            C     ISYM = .TRUE. IMPLIES SURFACE IS SYMMETRIC WITH RESPECT TO Y = 0.
000012            C     KMAX = MAXIMUM NUMBER OF ITERATIONS.
000013                  DATA TINY/1.E-20/, SMALL/1.E-12/, SAP1/4HSAP1/, STAR/4H****/
000014                  DATA EPSLN2/.01/,EPSLN3/1.0E-8/,IN/5/,IT/6/
000015                  DATA NOMORE/6HNOMORE/, DAMAGX/1.0/, DAMAGN/1.0/
000016            C
000017            C     IF THE ROUTINE DAMAGE IS CALLED UPON, THE SURFACE ZVN741,
000018            C     MUST BE READ IN BY MAIN. THIS CORRESPONDS TO LSURF = 5.
000019            C
000020            C
000021            C     ZEROING BLANK COMMON SINCE OVERLAID BY THE LOADER.
000022            C     LENGTH = TOTAL LENGTH OF BLANK COMMON.
000023            C
000024                  LENGTH = 792
000025                  DO  1001  I = 1, LENGTH
000026             1001 VIN(I,1) = 0.0
000027            C
000028            C     CALL EKEY($600,MAXTIM)
000029                  INITAL =.TRUE.
000030                  IXBASE = 0
000031                  IYBASE = 0
000032                  IZBASE = 0
000033                  IDEBUG = .TRUE.
000034                  LIMITQ = 10
000035                  VTEST = .05
000036                  CTEST = .05
000037            C
000038                  WRITE(IT,1) STAR,SAP1,STAR,SAP1,STAR,SAP1,STAR,SAP1,STAR,SAP1,STAR
000039                1 FORMAT(1H1, //,10X,5(A4,4X,A4,4X),A4  //)
000040                  READ(IN,2) (ISURF(L),L=1,NSURF)
000041                2 FORMAT(12I5)
000042                  WRITE(IT,3) (L,ISURF(L),L=1,NSURF)
000043                3 FORMAT(/ 2X,8(3X, 6HISURF(,I2,4H) = ,I1) /)
000044            C
000045            CALLING INPUT DATA FROM SUBROUTINE DATA.
000046                  CALL DATA
000047            C
000048            CALLING SURFACE INFORMATION FROM DRUM FILES.
000049                  DO  13  L = 1, NSURF
000050                  IF(ISURF(L).EQ.0)  GO TO 13
000051                  INPUT = L + 17
000052                  READ(INPUT,4) XLO,XHI,YLO,YHI,IXDIMN,IYDIMN,LL,ISYML,(SCALE(L,J)
000053                 1,J=1,3)
000054                4 FORMAT(4E8.4,3I4,L6,3E10.5)
000055                  IXDIM(L) = IXDIMN
000056                  IYDIM(L) = IYDIMN
000057                  ISYM(L) = ISYML
000058                  XLOW(L) = .9999998 * XLO
```

Figure 43a. M A I N Listing

```
000059                YLOW(L) = .9999998 * YLO
000060                XHIGH(L) = 1.0000002 * XHI
000061                YHIGH(L) = 1.0000002 * YHI
000062                XDELTA = (XHIGH(L)-XLOW(L))/(IXDIM(L)-1)
000063                YDELTA = (YHIGH(L)-YLOW(L))/(IYDIM(L)-1)
000064                WRITE(IT,5) L,XLO,XHI,YLO,YHI,XDELTA,YDELTA,IXDIMN,IYDIMN,LL,ISYML
000065               1,(L,J,SCALE(L,J),J=1,3)
000066              5 FORMAT(/13H FOR SURFACE ,I2,7H, XLO =,G11.4,7H, XHI =,G11.4,7H, YL
000067               10 =,G11.4,7H, YHI =,G11.4,10H, XDELTA =,G11.4,10H, YDELTA =,G11.4,
000068               2/9H  IXDIM =,I3,9H, IYDIM =,I3,5H, L =,I2,9H, ISYM = ,L1,5X,3(8H
000069               3SCALE(,I1,1H),,I1,3H) =,G10.2)/)
000070              6 FORMAT(/ 10X,8HIXBASE =,I3,5X,8HIYBASE = ,I3,5X,8HIZBASE =,I5 /)
000071        C
000072        CREATING X AND Y ARRAYS FROM INPUTTED INFORMATION.
000073        C
000074                IPONTR(L,1) = IXBASE + 1
000075              8 FORMAT(/ 5X,3(7HIPONTR(,I2,1H),I2,3H) =,I5,1H,5X)/)
000076                DO  9  I = 1, IXDIMN
000077              9 X(I + IXBASE) = XLO + (I-1)*XDELTA
000078                IXBASE = IXBASE + IXDIMN
000079                IPONTR(L,2) = IYBASE + 1
000080                DO  10  J = 1, IYDIMN
000081             10 Y(J+IYBASE) = YLO + (J-1)*YDELTA
000082                IYBASE = IYBASE + IYDIMN
000083                IPONTR(L,3) = IZBASE + 1
000084                WRITE(IT,   8)(L,J,IPONTR(L,J),J=1,3)
000085                MINC = IXDIMN * IYDIMN
000086                MINC2 = MINC + MINC
000087                JHI = IYDIMN - 1
000088                DO  12  I = 1, IXDIMN
000089                DO  12  J = 1, JHI, 2
000090                MS1 = I + (J-1)*IXDIMN + IZBASE
000091                MS2 = MS1 + IXDIMN
000092                ML1 = MS1 + MINC2
000093                ML2 = MS2 + MINC2
000094                READ(INPUT,11)(Z(KK),KK=MS1,ML1,MINC),(Z(KKK),KKK=MS2,ML2,MINC)
000095             11 FORMAT(6E13.7)
000096             12 CONTINUE
000097                IZBASE = IZBASE + 3*MINC
000098             13 CONTINUE
000099                WRITE(IT,6) IXBASE,IYBASE,IZBASE
000100                IF(IXBASE.GT.IXLIM.OR.IYBASE.GT.IYLIM.OR.IZBASE.GT.IZLIM) STOP
000101        C
000102             14 CONTINUE
000103        C       CALLING IN INPUT DATA
000104                READ(IN,15) MORE
000105             15 FORMAT(A6)
000106                WRITE(IT,17) MORE
000107                IF(MORE.EQ.NOMORE)CALL PLOTEM(3,VNIN,CNIN,VNOUT,CNOUT,NMAX,INITAL)
000108                PHIXL = EPSLON
000109                PHINL = EPSLON
000110                DAMAGX = 1.0
000111                DAMAGN = 1.0
000112                WRITE(IT,16)
000113             16 FORMAT(43H INPUT THE VALUE OF ISAME, USE FORMAT I3.   /)
000114             17 FORMAT(10X,A6)
000115                READ(IN,22) ISAME
000116                WRITE(IT,22) ISAME
000117                IF(ISAME.EQ.1) GO TO 75
000118                WRITE(IT,20)
```

Figure 43b. M A I N Listing (cont.)

```
000119              20 FORMAT(41H INPUT THE VALUE OF JMAX, USE FORMAT I3.  /)
000120                 READ(IN,22) JMAX
000121              22 FORMAT(I3)
000122                 WRITE(IT,24) JMAX
000123              24 FORMAT(33H THE VALUE OF JMAX AS READ IN IS , I3 /)
000124                 WRITE(IT,30)
000125              30 FORMAT(71H INPUT THE VALUES IN SEQUENCE OF J, CONFIG,NIN,NOUT,R,C,
000126                1 L, 4I3,3F12.4    /)
000127                 DO  32  J = 1, JMAX
000128                 READ(IN,34) I, ITABLE(J,1)        ,NIN(J),NOUT(J),R(J),C(J),FL(J)
000129              32 WRITE(IT,34)I, ITABLE(J,1)        ,NIN(J),NOUT(J),R(J),C(J),FL(J)
000130                 CALL SETUP(   NIN,NOUT,LBLOCK,JMAX,NMAX,JPARAL,LMEX)
000131              33 CONTINUE
000132              34 FORMAT(4I3, 3F12.4)
000133           C
000134           C     IF INKALL.NE. 1, PRINTING IS SUPPRESSED, EXCEPT FOR EVERY MMODTH
000135           C     TIME STEP.
000136                 WRITE(IT,41)
000137              41 FORMAT(41H INPUT THE VALUE OF INKALL AND MMOD, 2I3. /)
000138                 READ(IN,42) INKALL,MMOD
000139              42 FORMAT(2I3)
000140                 WRITE(IT,44) INKALL,MMOD
000141              44 FORMAT( 9H INKALL =,I2,10H,   MMOD =,I3     /)
000142           C
000143                 READ(IN,46) EPSLON
000144              46 FORMAT(F10.6)
000145                 WRITE(IT,48) EPSLON
000146              48 FORMAT(32H THE ITERATION CRITERIA,EPSLON =, G14.8 /)
000147           C
000148                 WRITE(IT,54)
000149              54 FORMAT(54H INPUT 1 IF INPUT VOLTAGE FIXED, 2 IF CURRENT, I3 FRMT/)
000150                 READ(IN,56) IFIXIN
000151              56 FORMAT(I3)
000152                 WRITE(IT,56) IFIXIN
000153                 WRITE(IT,58)
000154              58 FORMAT(52H INPUT 1 IF VOUT IS FIXED, 2 IF COUT. USE FORMAT I3./)
000155                 READ(IN,60) IFIXOT
000156              60 FORMAT(I3)
000157                 WRITE(IT,56) IFIXOT
000158                 KROSS = 2 - IABS(IFIXIN - IFIXOT)
000159                 WRITE(IT,61) IFIXIN, IFIXOT, KROSS
000160              61 FORMAT(/8H IFIXIN=,I1,9H, IFIXOT=,I1,8H, KROSS=,I1,/)
000161                 WRITE(IT,62)
000162              62 FORMAT(53H INPUT THE VALUE OF THE FIXED OUTPUT VARIABLE, F12.4./)
000163                 GO TO(68,64), IFIXOT
000164              64 READ(IN,65) CNOUT(NMAX)
000165                 WRITE(IT,65) CNOUT(NMAX)
000166              65 FORMAT(F12.4)
000167                 Y0 = CNOUT(NMAX)
000168                 GO TO 70
000169              68 READ(IN,65)VNOUT(NMAX)
000170                 WRITE(IT,65) VNOUT(NMAX)
000171                 Y0 = VNOUT(NMAX)
000172              70 CONTINUE
000173                 WRITE(IT,72)
000174              72 FORMAT(58H INPUT THE INITIAL VALUES OF VIN(1), CIN(1), USING 2F12.
000175                1 4   )
000176                 READ(IN,74) VNIN(1), CNIN(1)
000177                 WRITE(IT,74) VNIN(1),CNIN(1)
000178              74 FORMAT(2F12.6)
```

Figure 43c. M A I N Listing (cont.)

```
000179          C         READ FORCING FUNCTION DATA.
000180          C
000181          C     THE NEXT THREE STATEMENTS CAUSE INPUTTING OF DATA CARDS BY THE
000182          C     ROUTINES RADGEN, VOLTIM, AND PLOTEM.  IN ADDITION PLOT6 WILL ALSO
000183          C     BE CALLED BY PLOTEM AND WILL READ ONE DATA CARD.
000184          C     HOWEVER, IF THE RUN IS A SECONDS PASS OF DATA SETS, THIS CARD WILL
000185          C     NOT, REPEAT NOT, BE READ AND SO SHOULD NOT BE PLACED IN THE SECOND
000186          C     AND FOLLOWING DATA SETS.
000187          C
000188             75 CALL RADGEN(0,STIMUL,PHI,IRADX,IRADN)
000189                DUMMY = VOLTIM(0)
000190                IF(ISAME.NE.1) CALL PLOTEM(-1,VNIN,CNIN,VNOUT,CNOUT,NMAX,INITAL)
000191                NEXTAK=1
000192                GO TO (80,82), IFIXIN
000193             80 F1 = VNIN(1)
000194                G1 = CNIN(1)
000195                GO TO 90
000196             82 F1 = CNIN(1)
000197                G1 = VNIN(1)
000198          C
000199          CONVOKING THE SYSTEM ELAPSED TIME ROUTINE TO START THE CLOCK
000200           90    CALL ELT1
000201          C
000202          C     THE 90 DO LOOP STEPS TIME.
000203                DO  500  M = 1, MMAX
000204                MTRUN = M/MMOD
000205                MODM = MTRUN*MMOD/M
000206                GO TO (92,94), IFIXIN
000207             92 FOLD = VNIN(1)
000208                   G = CNIN(1)
000209                CALL RADGEN(1,VNIN(1),PHI,IRADX,IRADN)
000210                F = VNIN(1)
000211                GO TO 96
000212             94 FOLD = CNIN(1)
000213                   G = VNIN(1)
000214                CALL RADGEN(1,CNIN(1),PHI,IRADX,IRADN)
000215                F = CNIN(1)
000216             96 IF(IRADX.AND.PHI(1).GT.0.) PHIXL = ALOG10(PHI(1))
000217                IF(IRADN.AND.PHI(2).GT.0.) PHINL = ALOG10(PHI(2))
000218                IF(.NOT.(INKALL.EQ.1.OR.MODM.EQ.1))  GO TO 100
000219                WRITE(IT,97) M,TIME(MPRIME,1)
000220             97 FORMAT(/,6H0  M =,I5,10X,6HTIME =,G14.2)
000221                WRITE(IT,98)
000222             98 FORMAT(  76H  K     VIN          CIN          VOUT          COUT
000223               1   P          DPDX                    )
000224          C
000225          C     F = CURRENT VALUE OF FIXED INPUT VARIABLE
000226          C     G = CURRENT VALUE OF ADJUSTED INPUT VARIABLE.
000227          C     V = CURRENT VALUE OF ADJUSTED OUTPUT VARIABLE.
000228          C     YO= DESIRED VALUE OF ADJUSTED OUTPUT VARIABLE.
000229          C     P = PRODUCT OF TRANSFER FUNCTIONS OF ADJUSTED OUTPUT VARIABLE.
000230          C     AK = CURRENT GUESS OF ADJUSTED INPUT VARIABLE.
000231          C     AK1= PREVIOUS GUESS OF ADJUSTED INPUT VARIABLE
000232          C     AK2= PAST PREVIOUS GUESS OF ADJUSTED INPUT VARIABLE
000233          C
000234           103  IF(M.GT.1) GO TO 110
000235                DO  105  N1 = 1, NMAX
000236                IF(JPARAL(N1))  103, 105, 103
000237            103 N2 = LMEX(N1)
000238                DO  104  N3 = 1, N2
```

Figure 43d. M A I N Listing (cont.)

```
000239              LB = LBLOCK(N),N3)
000240            104 FACTOR(LB) = 1.0/N2
000241            105 CONTINUE
000242          C
000243          CALCULATING FIRST GUESS OF ADJUSTED INPUT VARIABLE AS LINEAR EXTRAPOLA-
000244          C TION OF LAST CONVERGED VALUE BY RATIO OF NEW AND OLD FIXED INPUT
000245          C VARIABLE.
000246            110 IF(NEXTAK.NE.0) GO TO 112
000247                NEXTAK = 1
000248            111 AK = F * G1/F1
000249                GO TO 120
000250            112 AK = G
000251                IF (F) 114, 116, 114
000252            114 IF(FOLD)  118, 111, 118
000253            116 AK = 0.0
000254                LPATH = 2
000255                NEXTAK = 0
000256                GO TO 160
000257            118 AK = G * F/FOLD
000258            120  IF(M.EQ.1.OR.LPATH.EQ.3) GO TO 140
000259                A = 0.50 * AK
000260                B = 1.50 * AK
000261                GO TO 145
000262            140 A = AK/EPSLON
000263                B = AK * EPSLON
000264            145 BNDLO = AMIN1(A,B)
000265                BNDHI = AMAX1(A,B)
000266                ITERAT = 0
000267          C
000268            150 CALL DRIVER (AK,V,BNDLO,BNDHI,INKALL,ITERAT,LPATH,YO,F,EPSLON)
000269          C 150 CALL NEWTON (AK,V,BNDLO,BNDHI,INKALL,ITERAT,LPATH,YO,F,EPSLON)
000270            160 GO TO(170,180), IFIXIN
000271            170  CNIN(1)=AK
000272                GO TO 185
000273            180 VNIN(1) = AK
000274            185 GO TO(200,190,190), LPATH
000275            190 DO  192  J = 1, JMAX
000276                VOUT(J,2) = VOUT(J,1)
000277            192 COUT(J,2) = COUT(J,1)
000278          C
000279          C     THE 200 DO LOOP CORRESPONDS TO INPUT NODES.
000280          C
000281            200  CONTINUE
000282                DO  300  N = 1, NMAX
000283                IF(JPARAL(N))  235,206,235
000284             206 LN = LMEX(N)
000285                J = LBLOCK(N,LN)
000286                IF(ABS(VNIN(N)).LT.TINY) VNIN(N) = SMALL
000287                IF(ABS(CNIN(N)).LT.TINY) CNIN(N) = SMALL
000288                VIN(J,1) = VNIN(N)
000289                CIN(J,1) = CNIN(N)
000290                ITRSAV = ITERAT
000291                NITER = 0
000292             207 NITER = NITER + 1
000293                ITERAT = ITRSAV * NITER
000294            209  VOLD = VOUT(J,1)
000295                COLD = COUT(J,1)
000296                IF(ABS(VOLD).LT.TINY) VOLD = SMALL
000297                IF(ABS(COLD).LT.TINY) COLD = SMALL
000298                GO TO (210,220), KROSS
```

Figure 43e. M A I N Listing (cont.)

```
000299          210 VOUT(J,1) = VIN(J,1) * FE(J)
000300              COUT(J,1) = CIN(J,1) * FI(J)
000301              GO TO 224
000302          220 VOUT(J,1) = CIN(J,1) * FE(J)
000303              COUT(J,1) = VIN(J,1) * FI(J)
000304          224 VTST = ABS ( 1.0 - VOUT(J,1)/VOLD )
000305              CTST = ABS ( 1.0 - COUT(J,1)/COLD )
000306              IF(.NOT.(ABS(VOLD).GT.0.)) VTST = 0.
000307              IF(.NOT.(ABS(COLD).GT.0.)) CTST = 0.
000308          226 IF ((VTST .GT. VTEST .OR. CTST .GT. CTEST) .AND. NITER.LE.LIMITQ
000309             1) GO TO 207
000310              ITERAT = ITRSAV
000311          230 IF ( ITERAT .GT. 1 ) GO TO 2301
000312              IF(IRADX) VOUT(J,3) =              PHIXL * FEPHI(J,1)
000313              IF(IRADN) VOUT(J,3) =              PHINL * FEPHI(J,2)
000314              IF(IRADX) COUT(J,3) =              PHIXL * FIPHI(J,1)
000315              IF(IRADN) COUT(J,3) =              PHINL * FIPHI(J,2)
000316              IF(IRADX) DAMAGX = DAMAGE(J,1)
000317              IF(IRADN) DAMAGN = DAMAGE(J,2)
000318              DAMAGT = DAMAGX * DAMAGN
000319         2301 IF(LPATH.EQ.1) GO TO 231
000320              IF(.NOT.(IRADX.OR.IRADN)) GO TO 231
000321              VOUT(J,1) = VOUT(J,1)*DAMAGT + VOUT(J,3)
000322              COUT(J,1) = COUT(J,1)*DAMAGT + COUT(J,3)
000323          231 IF(JPARAL(N)) 232,232,250
000324          232 VNOUT(N) = VOUT(J,1)
000325              CNOUT(N) = COUT(J,1)
000326              GO TO 250
000327          235 CALL PARLEL(N,LBLOCK,LMEX,FACTOR,CNOUT,VNOUT,VNIN,CNIN,
000328             1 INKALL,JPARAL)
000329              GO TO 230
000330          250  VNIN(N+1) = VNOUT(N)
000331               CNIN(N+1) = CNOUT(N)
000332          300   CONTINUE
000333      C
000334              GO TO (301,440,440), LPATH
000335          301 GO TO (302,304), KROSS
000336          302   FEPROD = VNOUT(NMAX)/VNIN(1)
000337                FIPROD = CNOUT(NMAX)/CNIN(1)
000338              GO TO 308
000339          304   FEPROD = VNOUT(NMAX)/CNIN(1)
000340                FIPROD = CNOUT(NMAX)/VNIN(1)
000341      C
000342          308 GO TO (310,314), IFIXOT
000343          310 P = FEPROD
000344              V = VNOUT(NMAX)
000345              GO TO 320
000346          314  P = FIPROD
000347              V = CNOUT(NMAX)
000348          320 IF(ITERAT-2) 322,324,324
000349          322 DPDX = 0.0
000350              AK1 = AK
000351              GO TO 328
000352          324 DP = P - POLD
000353              DX = AK - AK1
000354              IF(ABS(DX).LT.TINY) DX = SMALL
000355              DPDX = DP/DX
000356          328 IF(.NOT.(INKALL.EQ.1.OR.MODM.EQ.1))  GO TO 342
000357          330 WRITE(IT,340)ITERAT,VNIN(1),CNIN(1),VNOUT(NMAX),CNOUT(NMAX),P,DPDX
000358          340 FORMAT(1X,I3,1X,G11.4,1X,G13.6,1X,G11.4,1X,G12.5,1X,G10.3,1X,G11.4
```

Figure 43f. M A I N Listing (cont.)

```
000359                1)
000360              342 AK2 = AK1
000361                  AK1 = AK
000362                  POLD = P
000363            COMPLETION OF FUNCTION EVALUATION FOR ITERATION DRIVER.
000364                  GO TO 150
000365            C
000366              440 IF(.NOT.(INKALL.EQ.1.OR.MODM.EQ.1))  GO TO 450
000367                  WRITE(IT,441)
000368              441 FORMAT(// 128H  J    VIN(J)        CIN(J)      VOUT(J,1)     COUT(J,1
000369                 1)      VDIFF      CDIFF      VOUT(J,2)     COUT(J,2)     VOUT(J,3)     C
000370                 2OUT(J,3)    )
000371              444 DO  445  J = 1, JMAX
000372                  VDIFF = VIN(J,1)-VOUT(J,1)
000373                  CDIFF = CIN(J,1)-COUT(J,1)
000374              445 WRITE(IT,446)J,VIN(J,1),CIN(J,1),VOUT(J,1),COUT(J,1),VDIFF,CDIFF
000375                 1,VOUT(J,2),COUT(J,2),VOUT(J,3),COUT(J,3)
000376              446 FORMAT(I3,10(1X,G11.3))
000377              450 DO  480  J = 1, JMAX
000378                  DO  460  JIG = 2, JT
000379                           JOG = JT - JIG + 2
000380                     VIN(J,JOG) = VIN(J,JOG-1)
000381                     CIN(J,JOG) = CIN(J,JOG-1)
000382                  VINTGL(J,JOG) = VINTGL(J,JOG-1)
000383                  CINTGL(J,JOG) = CINTGL(J,JOG-1)
000384              460 CONTINUE
000385                  DO  470  JIG = 2, JD
000386                           JOG = JD - JIG + 2
000387                  VINDT1(J,JOG) = VINDT1(J,JOG-1)
000388                  CINDT1(J,JOG) = CINDT1(J,JOG-1)
000389              470 CONTINUE
000390              480 CONTINUE
000391                  CALL PLOTEM(0,VNIN,CNIN,VNOUT,CN. 'T,NMAX,INITAL)
000392              500 CONTINUE
000393              600 CALL ELT3(LTIME)
000394                  WRITE(IT,610) LTIME
000395              610 FORMAT(// 33H THE ELAPSED TIME REQUIRED WAS...,2A6 , //)
000396                  CALL PLOTEM(1,VNIN,CNIN,VNOUT,CNOUT,NMAX,INITAL)
000397                  CALL PLOTEM(2,VNIN,CNIN,VNOUT,CNOUT,NMAX,INITAL)
000398                  CALL RADGEN(2,STIMUL,FMI,IRADX,IRADN)
000399                  GO TO 14
000400                  END
```

Figure 43g. M A I N Listing (cont.)

brought in from drum files using a sequence of read statements which essentially treats the arrays as linear rather than triply dimensioned so that the different surfaces can have different dimensions if desired. Pointers are calculated and entered into the XYZ common block for use later by TSURF and SURFB. The first data card has the surface number; the array dimensions; the x, y, and z scaling factors; and the symmetry type, i.e. whether even or odd. Then follow the $(z,\partial z/\partial x,\partial z/\partial y)$ cards totaling NX times NY (or 200) in number.

Only those surface arrays are read from the drum files which are to be used in a given simulation. The specific arrays are designated by the first read, Format number 2. If a specific surface is needed in the computation and has not been read in, then computed GO TO's may go out of range during execution, and correct pointers will not exist for SURFB.

The data read statements that extend from the statement 14 to statement 74 bring in the information on the circuit needed for a given run. ISAME is a rerun variable for repeating the same circuit; zero means false or a new circuit, one means true or a rerun of the same circuit. JMAX is the number of blocks in the circuit. The read at Format 34 calls in J - the block sequence number ITABLE(J,1) indicates the circuit element as described by the comment cards in FE and FI. NIN(J) and NOUT(J) are the input and output node numbers for a block, while R(J), C(J), and FL(J) represent resistance, capacitance, or inductance values.

The following statement calls SETUP which ascertains the circuit configuration from the node numbers, and tags these blocks in parallel branches for treatment later during propagation by the parallel algorithm in PARLEL.

The following READ statements are self-explanatory as indicated by the comments in the WRITE FORMATS. IFIXIN and IFIXOT indicate to the program whether the voltage or current is the fixed input and output variables. From these the variable KROSS is calculated, which is used in many subroutines in computed GO TOs for switching from the crossed to uncrossed propagation strategy. The normal value for IFIXIN is one and that for IFIXOT is two. The usual value for CNOUT(NMAX) is zero. VNIN(1) and CNIN(1) are used on the first time step to initiate the iteration process. The remainder of the data card stream is read in by calls to RADGEN, VOLTIM, and PLOTEM.

3. SUBROUTINE RADGEN (N, STIMUL, PHI, IRADX, IRADN)

RADGEN creates the radiation stimulus applied to the device during the simulation. The listing of RADGEN is contained in Figure 44. Four classes of forcing functions can be used - constant, Gaussian, Weibull, or piecewise linear. Both neutron and X-ray stimulus functions can be generated simultaneously. Since the radiation response surfaces really were created by plotting response characteristics from experimental radiation facilities whose instantaneous dose varies during the radiation pulse, an "isodosal" line actually ranges in dose in the same manner as did the experimental pulse. In other words, the basic data were not deconvolved to true instantaneous dose.

The significance of this representation then is that a constant stimulus function will then represent a simulation of the radiation pulse from the accelerator or reactor which generated the basic data set itself. So a constant stimulus then moves back along an isodosal of the surface, and the resultant calculation is portrayal of the experimental oscilloscope waveform whose peak dosage value corresponds to the isodosal being sampled.

A still more important aspect of this representation is that this type of simulation does not require convolution of the radiation stimulus function in time since only one partition element need move back along the surface. If a different stimulus function is used, a family of partitions is created, one at each time step, and convolving of running sums at each time step is required. These partitions range over a dosage interval on the surface, sampling the structure over a large section of the surface. Hence, the result of the computation is an approximation to that which would be obtained if the original data set were deconvolved initially. In the next subsection we will show two calculations for the same dosage level with and without convolution. The results are surprisingly close to each other in general structure. The main result from the viewpoint of a computer oriented radiation simulation strategy is that simulation of the radiation facility type of exposure reduces the surface look-ups required by a factor of 25 to 50, and hence is fast in execution on the computer.

The above discussion provides a basis for understanding the logical variable KONVOL used in RADGEN and passed through the TIMEX COMMON block for use by the convolution subroutine CONVOL. The COMMON block listings are given in Figure 45.

```
@ ELT RADGEN,1,720302, 47814   , 1

000001                SUBROUTINE RADGEN (N,STIMUL,PHI,IRADX,IRADN)
000002                INCLUDE TIME,LIST
000003                DIMENSION RHO1(25),RHO2(25),T1(25),T2(25),PHI(2),XPHI(100,2),
                     1YPHI(100,2)
000005                DIMENSION ITYPE1(2),ITYPE2(2),NAME1(2),NAME2(2),IWEIBL(2),
000006               1IGAUSS(2),IPIECE(2),IXRAY(2),NEUTRN(2),NOPT(2)
000007                DIMENSION LABEL7(48),ILABEL(6,8),IPOINT(7),TITLE(12),
000008               1IORIGN(7),SKALE(7),LAWG(7),IPAR(2),IPOYNT(7)
000009                LOGICAL IRADX1,IRADN1,IRADX2,IRADN2,IRADX,IRADN,KONVOL
000010                DATA IN,IT/5,6/
000011                DATA IWEIBL(1)/6HWEIBUL/,IWEIBL(2)/6HL      /,IGAUSS(1)/6HGAUSSI/,
000012               1      IGAUSS(2)/6HAN     /,IXRAY(1)/6HXRAY  /,IXRAY(2)/6H       /,
000013               2      NEUTRN(1)/6HNEUTRO/,NEUTRN(2)/6HN      /,IPIECE(1)/6HPIECEW/,
000014               3      IPIECE(2)/6HISE    /,IBLANK/6H       /
000015                DATA IFXR/6HFXR    /,ISPR/6HSPR    /
000016                DATA  IPOYNT(1)/1H1/,IPOYNT(2)/1H2/,IPOYNT(3)/1H3/,IPOYNT(4)/1H4/,
000017               1      IPOYNT(5)/1H5/,IPOYNT(6)/1H6/,IPOYNT(7)/1HX/
000018          C THE DISTRIBUTION FORCING FUNCTIONS ARE CALCULATED BY USING THE
000019          C FOLLOWING STATEMENT FUNCTIONS.
000020                PWEIBL(TYME,ALPHA,BETA,GAMMA) = (BETA * ALPHA ** (-BETA)*(TYME -
000021               1  GAMMA) ** (BETA-1))** (((TYME-GAMMA)/ALPHA) ** BETA)
000022                PGAUSS(TYME,A,TAU,SIGMA)=(A/(SIGMA * (2*3.14159) ** 0.5))**
000023               1  (( TYME - TAU) ** 2 / (2 * SIGMA ** 2))
000024                PICWIS (RI,RIP1,TI,TIP1,PHIMAX,TYME) = ((RIP1 - RI) * (TYME - TI)
000025               1  /( TIP1 - TI ) + RI) * PHIMAX
000026          C
000027          C DATA ARE READ WHEN N = 0 .
000028          C
000029                IF (N - 1) 5, 100, 200
000030          C INITIALIZATION
000031              5 IRADX1 = .FALSE.
000032                IRADN1 = .FALSE.
000033                IRADX2 = .FALSE.
000034                IRADN2 = .FALSE.
000035                IRADX = .FALSE.
000036                IRADN = .FALSE.
000037                KONVOL(1) = .TRUE.
000038                KONVOL(2) = .TRUE.
000039                RADTIM = 0.0
000040                ILO = 1
000041                KOUNT1 = 0
000042                KOUNT2 = 0
000043                NUMBER = 0
000044          C
000045                READ(IN,10) ITYPE1(1),ITYPE1(2),NAME1(1),NAME1(2),B1,B2,B3
000046             10 FORMAT (4A6,6X,3F10.5)
000047                IF ( NAME1(1).EQ. IFXR .OR.NAME1(1).EQ.ISPR) RADTIM = B2
000048                IF (RADTIM .GT. 0.0) RADTLG = ALOG10(RADTIM)
000049                IF(ITYPE1(1).NE.IBLANK.AND.NAME1(1).NE.IFXR.AND.NAME1(1).NE.ISPR)
000050               1 NUMBER = NUMBER + 1
000051                IF (NAME1(1) .NE. IPIECE(1)) GO TO 35
000052                NSTEPS = B1
000053                WRITE (IT,15) NSTEPS
000054             15 FORMAT (9HNSTEPS = ,I3)
000055                DO  25  I = 1, NSTEPS
000056                READ(IN,20) RHO1(I),T1(I)
000057             20 FORMAT (2F10.5)
000058             25 WRITE(IT,30) I,RHO1(I),I,T1(I)
```

Figure 44a. R A D G E N Listing

```
000059              30 FORMAT( 6HRHO1( ,I3,5H ) = ,G12.5,5X,4HT1( ,I3,5H ) = ,G12.5)
000060                 NSTEP1 = NSTEPS - 1
000061              35 READ(IN,10) ITYPE2(1),ITYPE2(2),NAME2(1),NAME2(2),C1,C2,C3
000062                 IF ( NAME2(1).EQ. IFXR .OR.NAME2(1).EQ.ISPR) RADTIM = C2
000063                 IF(ITYPE2(1).NE.IBLANK.AND.ITYPE1(1).NE.ITYPE2(1).AND.NAME2(1)
000064                1.NE.IFXR.AND.NAME2(1).NE.ISPR) NUMBER = NUMBER + 1
000065                 IF(NAME2(1) .NE. IPIECE(1)) GO TO 60
000066                 NSTEPS = C1
000067                 WRITE (IT,15) NSTEPS
000068                 DO  40  I = 1, NSTEPS
000069                 READ(IN,20) RHO2(I), T2(I)
000070              40 WRITE(IT,30) I, RHO2(I), I, T2(I)
000071                 NSTEP2 = NSTEPS - 1
000072              60 WRITE(IT,65) ITYPE1(1),ITYPE1(2),NAME1(1),NAME1(2),B1,B2,B3
000073                 WRITE(IT,65) ITYPE2(1),ITYPE2(2),NAME2(1),NAME2(2),C1,C2,C3
000074              65   FORMAT(18H RADIATION TYPE = , 2A6, 5X, 15HDISTRIBUTION =
000075                1  2A6 / 5X
000076                2 32HTHE 3 RESPECTIVE PARAMETERS ARE ,3(4X,G12.5))
000077            C
000078                 IF(NUMREP - 1)  90, 660, 660
000079             660 READ(IN,670) (TITLE(J), J=1,12)
000080             670 FORMAT(8X,12A6)
000081                 READ(IN,675) SIZE,(LABEL7(J),J=1,48),IORIGN(7),SKALE(7),NUMBER,
000082                1 LAWG(7)
000083             675 FORMAT(A5,48A1,I3,3X,E12.5,I3,3X,I3)
000084                 DO  688  I = 1, NUMBER
000085             688 READ(IN,680) IPOINT(I),(ILABEL(I,J),J=1,8), IORIGN(I),SKALE(I),
000086                1 LAWG(I)
000087             680 FORMAT(A1,4X,8A6,I3,3X,E12.5,6X,I3)
000088            C
000089              90 IF (ITYPE1(1) .EQ. IXRAY(1)) IRADX1 = .TRUE.
000090                 IF (ITYPE1(1) .EQ.NEUTRN(1)) IRADN1 = .TRUE.
000091                 IF (ITYPE2(1) .EQ. IXRAY(1)) IRADX2 = .TRUE.
000092                 IF (ITYPE2(1) .EQ.NEUTRN(1)) IRADN2 = .TRUE.
000093                 IF (IRADX1 . OR. IRADX2) IRADX = .TRUE.
000094                 IF (IRADN1 . OR. IRADN2) IRADN = .TRUE.
000095            C
000096            C THE MEANING OF THE SUBSCRIPTS ON PHI AND KONVOL ARE AS FOLLOW
000097            C   1 = X-RAY   IRRADIATION
000098            C   2 = NEUTRON IRRADIATION
000099            C
000100                 IF ((NAME1(1) .EQ. IFXR .AND. ITYPE2(1) .EQ. IXRAY(1)) .OR.
000101                1    (NAME2(1) .EQ. IFXR .AND. ITYPE1(1) .EQ. IXRAY(1)) .OR.
000102                2    (NAME1(1) .EQ. ISPR .AND. ITYPE2(1) .EQ. NEUTRN(1)) .OR.
000103                3    (NAME2(1) .EQ. ISPR .AND. ITYPE1(1) .EQ. NEUTRN(1)))GO TO 900
000104                 IF(NAME1(1).EQ.IFXR.OR.NAME2(1).EQ.IFXR) KONVOL(1) = .FALSE.
000105                 IF(NAME1(1).EQ.ISPR.OR.NAME2(1).EQ.ISPR) KONVOL(2) = .FALSE.
000106                 RETURN
000107            C WHEN N = 1, DIFFERENT FORCING FUNCTIONS ARE CALCULATED AND RETURN
000108            C THE RESPECTIVE RESULTS TO THE CALLING PROGRAM.
000109              100 NN = N
000110                 STIMUL = VOLTIM(NN)
000111                 TIM = TIME(MPRIME,1)
000112                 K=1
000113                 IF (IRADX1) GO TO 110
000114                 IF (.NOT.IRADN1) GO TO 150
000115                 K=2
000116              110 IF (NAME1(1) .EQ. IWEIBL(1)) PHI(K) = PWEIBL(TIM ,B1,B2,B3)
000117                 IF (NAME1(1) .EQ. IGAUSS(1)) PHI(K) = PGAUSS(TIM ,B1,B2,B3)
000118                 IF(NAME1(1).EQ.IFXR.OR.NAME1(1).EQ.ISPR) PHI(K) = B1
```

Figure 44b. R A D G E N Listing (cont.)

```
000119                IF (NAME2(1) .EQ. IWEIBL(1)) PHI(L) = PWEIBL(TIM ,C1,C2,C3)
000120               1   + DELTA * PHI(K)
000121                IF (NAME2(1) .EQ. IGAUSS(1)) PHI(L) = PGAUSS(TIM ,C1,C2,C3)
000122               1   + DELTA * PHI(K)
000123                IF(NAME2(1).EQ.IFXR.OR.NAME2(1).EQ.ISPR) PHI(L) = C1
000124                IF (NAME2(1) .NE. IPIECE(1)) GO TO 200
000125                DO 180  I = ILO,NSTEP2
000126                IF((TIM.GT.T2(I).OR..NOT.TIM.LT.T2(I)).AND.TIM.LT.T2(I+1))GO TO190
000127             180 CONTINUE
000128                I = I - 1
000129             190 ILO = I
000130                IP1 = I + 1
000131                PHI(L) = PICWIS ( RHO2(I),RHO2(IP1),T2(I),T2(IP1),C2,TIM)
000132               1   + DELTA * PHI(K)
000133             200 RETURN
000134             900 WRITE (IT,910)
000135             910 FORMAT(55H   TERMINATED BY RADGN2 DUE TO INCONSISTENT DATA CARDS.)
000136                STOP
000137                END
```

Figure 44c. R A D G E N listing (cont.)

```
$ ELT COMMON,7,720302, 47791    , 4

000001          SAP* FCOPY
000002          C
000003                PARAMETER IX=10,JT=3,JD=3,IS=8
000004                COMMON/SAP/VIN(IX,JT),CIN(IX,JT),VINDTI(IX,JD),CINDTI(IX,JD),R(IX)
000005               1       ,FL(IX),C(IX),ITABLE(16,2),TKQ,CDIODE,RSDIOD,RPDIOD,EPSLON,S
000006               2       ,JEFLAG(IX),JIFLAG(IX),KROSS,VOUT(IX,3),COUT(IX,3)
000007               3       ,VINTGL(IX,JT),CINTGL(IX,JT),PHI(2),KSURF(16,IS),PHIXL
000008               4       ,PHINL,ITERAT
000009          C
000010                END
000011          TIME* FCOPY
000012          C
000013                PARAMETER LMAX = 100
000014                COMMON/TIMEX/MMAX,M,MPRIME,DT,DLOGT,RADTIM,TRAD,TRADLG,KONVOL(2)
000015               1,TIME(LMAX,2),DTL(LMAX,2),TL(LMAX,2),MODULO,MODE
000016          C
000017                END
000018          XYZ* FCOPY
000019          C
000020                PARAMETER IXLIM=100,IYLIM=100,IZLIM=6006,NSURF=12
000021                COMMON/XYZ/X(IXLIM),Y(IYLIM),Z(IZLIM),IPONTR(NSURF,3),ISYM(NSURF)
000022               1,XLOW(NSURF), XHIGH(NSURF), YLOW(NSURF), YHIGH(NSURF),IXDIM(NSURF)
000023               2,IYDIM(NSURF),SCALE(NSURF,3)
000024          C
000025                END
```

PROCEDURE NAME TABLE

SAP	00000000	TIME	00000214	XYZ	00000356

Figure 45. C O M M O N Listing

If the radiation data cards read in by RADGEN indicate that a SPR or FXR simulation is to be made, then KONVOL is set .FALSE. for the appropriate neutron or X-ray term. KONVOL is dimensioned two, with the first element denoting the X-ray term, and the second element denoting the neutron term.

The entries in the call list of RADGEN have the following meanings: N = 0 is an initialization call and causes data cards to be read, N = 1 is the normal entry on subsequent calls. STIMUL is the value of the voltage stimulation function obtained by a call to VOLTIM. PHI is an array of dimension two which returns the radiation forcing function values to MAIN. PHI(1) is the X-ray and PHI(2) the neutron dosage values. The logical variables IRADX and IRADN are set .TRUE. if a particular run requires X-ray or neutron simulation, and are passed back to MAIN through the call.

The actual READ statements of RADGEN, using FORMAT 10, as shown in Figure 44, read in the control variables ITYPE and NAME which denote type of radiation, X-ray or neutron, and the name of the distribution function by which it is to be represented as given above. IFXR or ISPR is the NAME applied for those simulations. The constants B1, B2, and B3 are used to bring in the peak dose level, radiation distribution time, location parameter, and the distribution width parameter.

If a piecewise linear radiation function is called for, then pairs of (dosage, time) points are read in. If the radiation dose level is generated by the distribution function or the piecewise representation, plot title and control information is read in by statements 660 through 680. This will cause PLOT6 to make printer and machine plots of the radiation forcing function.

4. FUNCTION SUBPROGRAM VOLTIM

Data cards are read in by VOLTIM as indicated by the listing of Figure 46. These permit a sinusoidal or piecewise linear voltage forcing function to be created by VOLTIM. In addition one data card is read in at statement 40 which reads the start and stop times, the radiation start time, the number of time steps, the option setting and the mode of the time base - that is whether linear or logarithmic.

An important function performed by VOLTIM is to load the TIME and DTL arrays which are used in the convolution calculations by CONVOL. The first columns in these arrays contain the values of time and differential time dt in a linear

```
@ ELT VOLTIM,1,720302, 50484    , 1

000001                  FUNCTION VOLTIM(N)
000002                  INCLUDE TIME,LIST
000003                  DIMENSION V(12), T(12)
000004                  DIMENSION TUNIT(3), TSCALE(3)
000005                  INTEGER OPTION,OPTLIN,OPTLOG,TUNIT,UNIT
000006                  DATA IN,IT/5,6/
000007                  DATA NANSEC/6HNANO S/,MICSEC/6HMICROS/,MILSEC/6HMILLIS/
000008                  DATA OPTLOG/6HLOG   /,OPTLIN/6HLINEAR/
000009            C
000010                  IF (N.NE.0) GO TO 50
000011                  ILO = 1
000012                  MODULO = 0
000013                  OLDTIM = 0.0
000014                  OLDLOG = 0.0
000015                  TRADLG = 0.0
000016                  READ (IN,10)IOPT
000017               10 FORMAT(I3)
000018                  WRITE (IT,17)IOPT
000019               17 FORMAT(26H0FORCING FUNCTION OPTION =,I3)
000020                  GO TO (18,30), IOPT
000021               18 READ (IN,12)A,FREQ
000022               12 FORMAT(2(E15.8,5X))
000023                  WRITE (IT,19)A,FREQ
000024               19 FORMAT(3H0A=E15.8,5X,6H FREQ=,E15.8)
000025                  OMEGA = 2.0*3.141592654*FREQ
000026                  GO TO 40
000027               30 READ(IN,10) NSTEPS
000028                  WRITE(IT,31) NSTEPS
000029               31 FORMAT(//69H A PIECEWISE LINEAR FORCE FUNCTION IS USED WITH THE NU
000030                 1MBER OF STEPS = ,I3,/ 31H  FUNCTION      TIME      UNIT  )
000031                  DO  36  I = 1, NSTEPS
000032                  READ(IN,34)  V(I),T(I), UNIT
000033                  WRITE(IT,35) V(I),T(I), UNIT
000034               34 FORMAT(2E12.8,A6)
000035               35 FORMAT(2X,2G12.4,A6)
000036                  IF(UNIT.EQ.NANSEC) TSC = 1.0
000037                  IF(UNIT.EQ.MICSEC) TSC = 1.0E+3
000038                  IF(UNIT.EQ.MILSEC) TSC = 1.0E+6
000039                  IF(UNIT.NE.NANSEC.AND.UNIT.NE.MICSEC.AND.UNIT.NE.MILSEC)
000040                 1 WRITE(IT,38)
000041               36 T(I) = T(I) * TSC
000042               38 FORMAT(5X, 50H THE UNIT MULTIPLIER IS NOT CORRECT FOR THE TIME. )
000043                  NSTEP1 = NSTEPS - 1
000044               40  READ(IN,41) ISTART,TUNIT(1), ISTOP, TUNIT(2), IRADTM, TUNIT(3),
000045                 1MMAX, OPTION
000046               41 FORMAT(5X,3(I6,1X,A6,2X),5X,I5,5X,A6)
000047                  WRITE(IT,41)ISTART,TUNIT(1), ISTOP, TUNIT(2), IRADTM, TUNIT(3),
000048                 1MMAX, OPTION
000049                  DO  42  K = 1,3
000050                  IF (TUNIT(K) .EQ. NANSEC) TSCALE(K) = 1.0
000051                  IF (TUNIT(K) .EQ. MICSEC) TSCALE(K) = 1.0E+3
000052                  IF (TUNIT(K) .EQ. MILSEC) TSCALE(K) = 1.0E+6
000053                  IF(TUNIT(K).NE.NANSEC.AND.TUNIT(K).NE.MICSEC.AND.TUNIT(K).NE.MILSE
000054                 1C) WRITE(IT,38)
000055               42 CONTINUE
000056                  TSTART = ISTART * TSCALE(1)
000057                  TSTART = AMAX1(TSTART,1.)
000058                  TSTOP  = ISTOP  * TSCALE(2)
```

Figure 46a. V O L T I M Listing

```
000059                RADTIM = IRADTM * TSCALE(3)
000060                IF (OPTION .EQ. OPTLIN) MODE = 1
000061                IF (OPTION .EQ. OPTLOG) MODE = 2
000062                WRITE (IT,46) OPTION
000063                IF(OPTION.NE.OPTLIN.AND.OPTION.NE.OPTLOG) STOP
000064             46 FORMAT(10X,A6,21H TIME STEPS ARE USED.  / )
000065                GO TO (47,48), MODE
000066             47 A1 = TSTART
000067                A2 = (TSTOP - TSTART) / (MMAX - 1)
000068                RETURN
000069             48 A1 = ALOG10(TSTART)
000070                A2 = (ALOG10(TSTOP/TSTART))/(MMAX - 1)
000071                RETURN
000072          C
000073          C     ENTRY POINT ON ALL BUT FIRST CARD READ OPERATION
000074          C     MODE = 1 CORRESPONDS TO  A  LINEAR  TIME BASE.
000075          C     MODE = 2 CORRESPONDS TO LOGARITHMIC TIME BASE.
000076          C
000077             50 MPRIME = M - MODULO * LMAX
000078                IF(MPRIME.EQ.LMAX) MODULO = MODULO + 1
000079                GO TO (52,54), MODE
000080             52 TIME(MPRIME,1) = AMAX1((A1+(M-1)*A2),1.)
000081                TIME(MPRIME,2) = ALOG10(TIME(MPRIME,1))
000082                GO TO 55
000083             54 TIME(MPRIME,2) = A1 + (M-1) * A2
000084                TIME(MPRIME,1) = 10.0**TIME(MPRIME,2)
000085             55 IF(M-1) 1055, 1055, 4055
000086           1055 GO TO(2055,3055), MODE
000087           2055 DT = A2
000088                DLOGT = ALOG10(DT)
000089                GO TO 5055
000090           3055 DLOGT = A2
000091                DT = 10.0**DLOGT
000092                GO TO 5055
000093           4055 DT = TIME(MPRIME,1) - OLDTIM
000094                DLOGT = TIME(MPRIME,2) - OLDLOG
000095           5055 OLDTIM = TIME(MPRIME,1)
000096                OLDLOG = TIME(MPPIME,2)
000097                DTL(MPRIME,1) = DT
000098                DTL(MPRIME,2) = DLOGT
000099                TRAD = TIME(MPRIME,1) - RADTIM
000100                TRADLG = ALOG10(AMAX1(TRAD,1.))
000101                IHI = MPRIME
000102                IF(MODULO.GT.0) IHI = LMAX
000103                DO  56  I = 1, IHI
000104                TL(I,1) = TIME(MPRIME,1) - TIME(I,1)
000105             56 TL(I,2) = TIME(MPRIME,2) - TIME(I,2)
000106          C
000107             58 GO TO(59,60), IOPT
000108             59 VOLTIM = A* SIN(OMEGA*TIME(MPRIME,1))
000109                RETURN
000110             60 DO  70  I = ILO, NSTEP1
000111                IF((TIME(MPRIME,1).GT.T(I).OR..NOT.TIME(MPRIME,1).LT.T(I)).AND.
000112               1 TIME(MPRIME,1).LT. T(I+1))  GO TO 80
000113             70 CONTINUE
000114                I = I - 1
000115             80 ILO = I
000116                VOLTIM =(V(I+1)-V(I))*(TIME(MPRIME,1)-T(I))/(T(I+1)-T(I)) + V(I)
000117            200 RETURN
000118                END
```

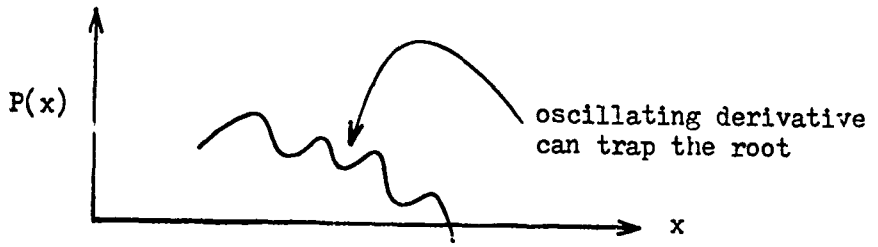
Figure 46b. V O L T I M Listing (cont.)

representation, while the second column contains the same in a logarithmic basis. These arrays are moduloed down to a maximum size of LMAX if the number of time steps exceeds LMAX. An interesting aspect of convolutional computational methods is that the response of old stimuli fade away as the partitions reach the flat portions of the surface; hence, a restricted prior time span is usually quite sufficient. Thus, LMAX does not need to be more than a few hundred.

5. SUBROUTINE DRIVER

DRIVER is essentially a Newton-Raphson iteration routine which has added features to attempt to cope with some of the problems that occur in a zero-finding problem such as this. The routine looks for sign changes on the function P versus variations in the iterate, which is the adjusted input variable x. When a sign change occurs, an upper or lower bound is moved in to contain the iterate. This is normally a wise strategy provided the root does not slide with the iterate, as may happen in some non-linear problems. Root sliding can also occur if the iteration process has terms carrying over from prior iterates or time steps (the computational delay problem). The listing of DRIVER is given in Figure 47.

Another difficult class of problem for an iteration driver routine is the case of an oscillating derivative accompanied by no zero crossing. The iterate is then trapped at a local minimum, and cannot escape. The strategy employed here is to allow so many trials which do not yield a sign change, and then to initiate a step and search procedure which expands the iteration zone by an arbitrary factor.



The expansion of the search zone can lead to an instability in the iteration process. The situation is improved if the function P is relatively free of pathological dependencies on the computational process. Care in arranging statements that compute transfer functions proved of significance in this regard, so that an intrinsic computational delay does not lead to oscillations on the next iterate.

```
@ ELT DRIVER,1,720302, 47802    , 1
000001                SUBROUTINE DRIVER(XITER,FUNCT,LWRBND,UPRBND,IPRINT,ITERAT,LPATH,  DRI
000002               1 YO,F,EPSLON)
000003          C
000004          C     STEWART RESEARCH ENTERPRISES, 23376 BELVOIR DR., LOS ALTOS, CALIF.
000005          C
000006          C     ITERATION DRIVER FOR MAIN.
000007          C
000008                DIMENSION ROOTS(3)
000009                REAL LWRBND
000010                LOGICAL SKIP
000011                DATA SKIP/.TRUE./,ITNMAX/35/,RATIO/1000./,ETA/2.E-6/
000012                DATA IT/6/ ,CHANGE/.5/
000013                DATA MAXR/3/,NS/0/,ROOTS(1)/0.0/,ROOTS(2)/0.0/,NFOUND/2/,NTOTAL/1/
000014                DATA TINY/1.E-20/, SMALL/1.E-12/
000015          C
000016                IF(ITERAT.NE.0) GO TO 243
000017          C
000018          C     FIRST PASS. USE GIVEN ITERATE.
000019          C
000020                NHELP = 0
000021              5 DELTA=(UPRBND-LWRBND)/(RATIO*XITER)
000022                GR = XITER/(1.+DELTA)
000023                NRTS=MIN0(NTOTAL,MAXR)
000024                WRITE(IT,7)
000025              7 FORMAT(1H+,80X,4H    M,9X,3HRLX,9X,3HRUX,10X,4HPOLE)
000026                IF (NRTS.GT.0) GO TO 9
000027                WRITE (6,8)NFOUND,NTOTAL,MAXR
000028              8 FORMAT(22H0ZERO ROOTS REQUESTED.,3I6)
000029                GO TO 300
000030              9 N4=NFOUND
000031                NXG=1                                                          NEWRO
000032                DX=(UPRBND-LWRBND)/20.                                         NEWRO
000033                DX=DX*1.0000001
000034                IPOLE=0
000035                POLE=LWRBND                                                    NEWRO
000036                RLX=LWRBND
000037                RUX=UPRBND
000038             10 GR=AMAX1(GR,LWRBND)                                            NEWRO
000039                XITER=GR*(1.0+DELTA)
000040                ITN=0
000041                NBK=0                                                          NEWRO
000042                IFV=0                                                          NEWRO
000043                M=1                                                            NEWRO
000044                GO TO 240                                                      NEWRO
000045          C
000046          C     2ND PASS. ITERATE IS RATIO OF FIRST DEPENDING ON BOUNDS.
000047          C
000048             15 X1=XITER                                                       NEWRO
000049                Y1=FUNCT                                                       NEWRO
000050                L1=NS                                                          NEWRO
000051                XITER=GR                                                       NEWRO
000052                M=2                                                            NEWRO
000053                GO TO 240                                                      NEWRO
000054          C
000055          C     3RD PASS. USE NEWTONS METHOD.
000056          C
000057             20 X2=XITER                                                       NEWRO
000058                Y2=FUNCT                                                       NEWRO
```

Figure 47a. D R I V E R Listing

```
000059                L2=NS                                                  NEWRO
000060                GO TO 90                                               NEWRO
000061          C
000062          C     4TH AND FOLLOWING PASSES.  LOOK FOR ZERO CROSSINGS.
000063          C
000064             25 IF (NBK.EQ.1) GO TO 65                                 NEWRO
000065                IF (FUNCT*Y2) 35,35,30                                 NEWRO
000066             30 IF (FUNCT*Y1) 35,35,65                                 NEWRO
000067          C     IF FIND ONE, SET NBK = 1
000068             35 NBK=1                                                  NEWRO
000069                IF (X1.LT.X2) GO TO 40                                 NEWRO
000070                X=X1                                                   NEWRO
000071                X1=X2                                                  NEWRO
000072                X2=X                                                   NEWRO
000073                Y=Y1                                                   NEWRO
000074                Y1=Y2                                                  NEWRO
000075                Y2=Y                                                   NEWRO
000076                L=L1                                                   NEWRO
000077                L1=L2                                                  NEWRO
000078                L2=L                                                   NEWRO
000079             40 IF (X1.LT.XITER) GO TO 45                              NEWRO
000080                X=XITER                                                NEWRO
000081                XITER=X1                                               NEWRO
000082                X1=X                                                   NEWRO
000083                Y=FUNCT                                                NEWRO
000084                FUNCT=Y1                                               NEWRO
000085                Y1=Y                                                   NEWRO
000086                L=NS                                                   NEWRO
000087                NS=L1                                                  NEWRO
000088                L1=L                                                   NEWRO
000089             45 IF (X2.LT.XITER) GO TO 50                              NEWRO
000090                X=X2                                                   NEWRO
000091                X2=XITER                                               NEWRO
000092                XITER=X                                                NEWRO
000093                Y=Y2                                                   NEWRO
000094                Y2=FUNCT                                               NEWRO
000095                FUNCT=Y                                                NEWRO
000096                L=L2                                                   NEWRO
000097                L2=NS                                                  NEWRO
000098                NS=L                                                   NEWRO
000099             50 IF (Y1*Y2) 55,55,60                                    NEWRO
000100          C
000101          C     MOVE BOUNDS, RLX AND RUX, IF HAVE CROSSING.
000102          C     MOVING BOUNDS AS CLOSE IN ON CROSSING CAN BE BAD IF FUNCTION IS
000103          C     PATHOLOGICAL SUCH THAT ROOT SLIDES WITH ITERATE.
000104          C
000105             55 RLX=X1                                                 NEWRO
000106                RLY=Y1                                                 NEWRO
000107                NRL=L1                                                 NEWRO
000108                RUX=X2                                                 NEWRO
000109                RUY=Y2                                                 NEWRO
000110                NRU=L2                                                 NEWRO
000111                GO TO 90                                               NEWRO
000112             60 RLX=X2                                                 NEWRO
000113                RLY=Y2                                                 NEWRO
000114                NRL=L2                                                 NEWRO
000115                RUX=XITER                                              NEWRO
000116                RUY=FUNCT                                              NEWRO
000117                NRU=NS                                                 NEWRO
000118                X1=RLX                                                 NEWRO
```

Figure 47b. D R I V E R Listing (cont.)

```
000119              Y1=RLY                                                    NEWRO
000120              L1=NRL                                                    NEWRO
000121              X2=RUX                                                    NEWRO
000122              Y2=RUY                                                    NEWRO
000123              L2=NRU                                                    NEWRO
000124              GO TO 90                                                  NEWRO
000125           65 X1=X2                                                     NEWRO
000126              Y1=Y2                                                     NEWRO
000127              L1=L2                                                     NEWRO
000128              X2=XITER                                                  NEWRO
000129              Y2=FUNCT                                                  NEWRO
000130              L2=NS                                                     NEWRO
000131              IF (NBK.EQ.0) GO TO 90                                    NEWRO
000132              IF (FUNCT) 70,70,80                                       NEWRO
000133           70 IF (RLY) 75,75,85                                         NEWRO
000134           75 RLX=XITER                                                 NEWRO
000135              GO TO 90                                                  NEWRO
000136           80 IF (RUY) 75,75,85                                         NEWRO
000137           85 RUX=XITER                                                 NEWRO
000138         C 90 ITN=ITN+1
000139           90 T1=Y1
000140              T2=Y2
000141              IF(SKIP) GO TO 94
000142              I=MAX0(L1,L2)
000143              T1=Y1*2.**(L1-I)                                          NEWRO
000144              T2=Y2*2.**(L2-I)                                          NEWRO
000145           94 M=3                                                       NEWRO
000146              IF (T2-T1) 100,95,100                                     NEWRO
000147           95 XITER=X1+.5*(X2-X1)                                       NEWRO
000148              GO TO 105                                                 NEWRO
000149         C
000150          100 X2MX1 = X2 - X1
000151              T2MT1 = T2 - T1
000152              IF(ABS(T2MT1).LT.TINY.AND.ABS(X2MX1).GT.(T2MT1/SMALL)) T2MT1=SMALL
000153         C
000154         C    BASIC ITERATION EQUATION.
000155              XITER = X1 - T1 * X2MX1/T2MT1
000156         C
000157              IF (NBK.EQ.1) GO TO 110                                   NEWRC
000158          105 IF (XITER.LT.LWRBND.OR.XITER.GT.UPRBND) GO TO 200
000159          110 NTEST=2                                                   NEWRC
000160              IF (ABS(XITER-X2).LT.ETA*ABS(XITER)) GO TO 125
000161              IF(ABS(FUNCT).LT.EPSLON*ABS(XITER).AND.ITERAT.GE.2) GO TO 135
000162              IF (NBK.EQ.0) GO TO 130                                   NEWRO
000163              IF (RLX-XITER) 115,240,120                                NEWRO
000164          115 IF (XITER-RUX) 240,240,120                                NEWRO
000165         C
000166         C    RESETTING ITERATE IF OUTSIDE OF BOUNDS.
000167         C
000168          120 XITER=(RLX+RUX)/2.                                        NEWRO
000169              GO TO 240                                                 NEWRO
000170          125 IF (ABS(XITER-X1).LT.ETA * ABS(XITER)) GO TO 135
000171              IF((T1*T2).LT.0.) XITER=X1+.8*(X2-X1)
000172          130 M=3                                                       NEWRO
000173              IF (ITN-15 ) 240,240,200
000174          135 IF(ABS(FUNCT).GT.ABS(XITER)) GO TO 200
000175         C
000176         C    ROOT FOUND.
000177         C
000178              N4=MIN0(N4+1,MAXR)                                        NEWRC
```

Figure 47c. D R I V E R Listing (cont.)

```
000179                ROOTS(N4)=XITER                                          NEWRO
000180                GR=AMAX1(.8*ABS(XITER),1.5*LWRBND)                       NEWRO
000181                IF(IPRINT.NE.0)
000182               1WRITE (6,140)XITER,ITN,IFV,NTEST
000183           140 FORMAT(7H ROOT =,E14.8,5X,6HITNS =,I3,5X,6HEVAL =,I3,5X,8HTEST NO.NEWRO
000184              1,I2,60X,3H***)                                           NEWRO
000185                IFV=0                                                    NEWRO
000186                IPOLE=0
000187                RLX=0.                                                   NEWRO
000188                RUX=0.                                                   NEWRO
000189                NBK=0                                                    NEWRO
000190                ITN=0
000191                IF (NRTS-N4) 145,145,10                                  NEWRO
000192           C                                                             NEWRO
000193           C     SORT THE ROOTS IN ASCENDING ORDER.                      NEWRO
000194           C                                                             NEWRO
000195             1 5 N7=N4-1                                                 NEWRO
000196                IF (N7.LE.0) GO TO 155                                   NEWRO
000197                DO 150 I=1,N7                                            NEWRO
000198                K=I+1                                                    NEWRO
000199                DO 150 J=K,N4                                            NEWRO
000200                IF (ROOTS(I).LT.ROOTS(J)) GO TO 150                      NEWRO
000201                T1=ROOTS(I)                                              NEWRO
000202                ROOTS(I)=ROOTS(J)                                        NEWRO
000203                ROOTS(J)=T1                                              NEWRO
000204           150 CONTINUE                                                  NEWRO
000205           155 IF (N4.GE.MAXR) GO TO 295                                 NEWRO
000206           C                                                             NEWRO
000207           C     CHECK INTERVALS BETWEEN ROOTS FOR SIGN CROSSINGS.       NEWRO
000208           C                                                             NEWRO
000209                ITN=0
000210                I=NXG-1                                                  NEWRO
000211                M=6                                                      NEWRO
000212                NBK=1                                                    NEWRO
000213           160 I=I+1                                                     NEWRO
000214                NXG=I                                                    NEWRO
000215                IF (I.GT.N4) ROOTS(I)=UPRBND                             NEWRO
000216                IF (I.EQ.1) GO TO 165                                    NEWRO
000217                XITER=ROOTS(I-1)*1.001                                   NEWRO
000218                X=(ROOTS(I)-ROOTS(I-1))/9.99                             NEWRO
000219                IF (X.LT..01) GO TO 195                                  NEWRO
000220                IF (M-6) 240,240,175                                     NEWRO
000221           165 X=(ROOTS(1)-LWRBND)/9.99                                  NEWRO
000222                IF (X.LT..01) GO TO 195                                  NEWRO
000223                XITER=LWRBND                                             NEWRO
000224                GO TO 240                                                NEWRO
000225           170 X=XITER                                                   NEWRO
000226                Y2=FUNCT                                                 NEWRO
000227                L2=NS                                                    NEWRO
000228           175 DO 190 J=1,10                                             NEWRO
000229                XITER=AMIN1(XITER+X,UPRBND)                              NEWRO
000230                M=7                                                      NEWRO
000231                GO TO 240                                                NEWRO
000232           180 IF (Y2*FUNCT) 60,60,185                                   NEWRO
000233           185 X2=XITER                                                  NEWRO
000234                Y2=FUNCT                                                 NEWRO
000235                L2=NS                                                    NEWRO
000236           190 CONTINUE                                                  NEWRO
000237           195 IF (I.GT.N4) GO TO 295                                    NEWRO
000238                IF (I-NRTS) 160,295,295                                  NEWRO
```

Figure 47d. D R I V E R Listing (cont.)

```
000239          C                                                              NEWRO
000240          C     SEARCH FOR A MORE SUITABLE GUESS.                        NEWRO
000241          C                                                              NEWRO
000242            200 IF (NHELP .GT.4) GO TO 145                                NEWR
000243                NHELP = NHELP + 1
000244                ITN=0
000245                NBK = 0
000246          C
000247          C     MAYBE TRAPPED BY SLIDING ROOF. FIRST TRY MOVING BOUNDS OUT.
000248          C
000249                CHANGE = CHANGE **NHELP
000250                IF(XITER) 202,202,203
000251            202 LWRBND = LWRBND / CHANGE
000252                UPRBND = UPRBND * CHANGE
000253                GO TO 204
000254            203 LWRBND = LWRBND * CHANGE
000255                UPRBND = UPRBND / CHANGE
000256            204 RLX = LWRBND
000257                RUX = UPRBND
000258                POLE= LWRBND
000259                DX= (UPRBND - LWRBND)/20.0
000260                IF(NHELP.LE.2) GO TO 65
000261          C
000262          C     NOW TRY SYSTEMATIC STEPPING. (PUSH THE PANIC BUTTON).
000263          C
000264                XITER=POLE                                               NEWRC
000265                IF (IPOLE.NE.0) GO TO 201
000266                IPOLE=1
000267                M=4                                                      NEWRC
000268                GO TO 240                                                NEWRC
000269            201 FUNCT=RFUNCT
000270                NS=NNR
000271            205 X2=XITER                                                 NEWRC
000272                Y2=FUNCT                                                 NEWRC
000273                L2=NS                                                    NEWRC
000274                M=5                                                      NEWRC
000275            210 POLE=AMIN1(POLE+DX,UPRBND)                               NEWRC
000276                XITER=POLE                                               NEWRC
000277                GO TO 240                                                NEWRC
000278            215 X1=X2                                                    NEWRC
000279                Y1=Y2                                                    NEWRC
000280                L1=L2                                                    NEWRC
000281                X2=XITER                                                 NEWRC
000282                Y2=FUNCT                                                 NEWRC
000283                L2=NS                                                    NEWRC
000284                RFUNCT=FUNCT
000285                NNR=NS
000286                IF (Y1*Y2) 25,25,220                                     NEWRI
000287            220 IF (L2-L1) 90,225,230                                    NEWRI
000288            225 IF (ABS(Y2)-ABS(Y1)) 90,230,230                          NEWRI
000289            230 IF (XITER-UPRBND) 210,235,235                            NEWRI
000290            235 NHELP=1                                                  NEWRI
000291                GO TO 145                                                NEWRI
000292          C                                                              NEWRI
000293          C     COMPUTE FUNCTION AND DIVIDED FUNCTION.                   NEWRI
000294          C                                                              NEWRI
000295            240 IF (XITER.GT.UPRBND) GO TO 200                           NEWRI
000296                NTEST=1                                                  NEWRI
000297                IFV=IFV+1                                                NEWRI
000298                ITN = ITN + 1
```

Figure 47e. D R I V E R Listing (cont.)

```
000299                ITERAT=ITERAT + 1
000300                LPATH=1
000301                RETURN
000302          C     RETURN FOR FUNCTION EVALUATION.
000303          C
000304          C     ENTRY POINT WITH NEW FUNCTION VALUE.
000305          C
000306           243  IF(ITERAT.GE.ITNMAX) GO TO 296
000307                WRITE(IT,244) M,RLX,RUX,POLE
000308             244 FORMAT(1H ,83X,I1,4X,3(G12.4))
000309                T1=FUNCT
000310                N2=NS                                                  NEWR0
000311                 IF(FUNCT.EQ.0.0.AND.XITER.NE.0.0) GO TO 135
000312             245 IF (N4.EQ.0) GO TO 255                                NEWR0
000313          C
000314          C     SCALER IS NEEDED WHEN FUNCTION VALUES TAKE ON EXTREME VALUES DUE
000315          C     TO DIVIDING BY ROOTS ALREADY FOUND, IN CASES OF MULTIPLE ROOTS.
000316          C
000317          C     IF SCALER IS REQUIRED, SET  SKIP = .FALSE.
000318                IF(SKIP) GO TO 275
000319                DO 250 L=1,N4                                          NEWR(
000320                FUNCT=FUNCT/(XITER-ROOTS(L))                           NEWR(
000321                CALL SCALER(FUNCT,J)
000322             250 NS=NS+J                                               NEWR(
000323              255  IF(IPRINT) 260,270,260
000324               260 WRITE (6,265)XITER,FUNCT,NS,T1,N2,M,RLX,RUX
000325               265 FORMAT(E20.8,5X,2(E9.3,I4),I8,5X,2E15.8)
000326               270 IF (FUNCT) 275,260,275
000327          C
000328          C     BASIC STEERING SWITCH TO DIFFERENT STRATEGIES.
000329          C
000330               275 GO TO (15,20,25,205,215,170,180),M                  NEWR(
000331               280 NTEST=6                                             NEWR(
000332                   GO TO 135
000333               295 NTOTAL=N4                                           NEWR(
000334              296  IF(ITERAT.GE.ITNMAX) WRITE(IT,298)
000335              298  FORMAT(36H  DRIVER ITERATION MAXIMUM EXCEEDED.)
000336              300  LPATH=2
000337                   IF(ITERAT.GE.ITNMAX) LPATH=3
000338                   RETURN
000339          C 300 RETURN
000340          C        TERMINATION TESTS                                    NEWR(
000341          C          1 = NORMAL ROOT ACCEPTANCE,  F(X)=0.
000342          C          2 = NORMAL CONVERGENCE TO EPSLON
000343          C          3 = MAXIMUM ITERATION COUNT (100) EXCEEDED.      NEWR(
000344          C          6 = DIVIDED RESIDUAL WENT TO ZERO (CAUSED BY MULTIPLE ROOTS).NEWR(
000345                END                                                    NEWR(
```

Figure 47f. D R I V E R Listing (cont.)

For certain types of zero-finding problems, such as polynomial evaluations, more than one root may exist over the range of variation of the iterate. In such cases DRIVER divides the original function P by the root already found, creating a new function which does not have the old root inherently contained within the iteration zone. Such a situation is shown in Figure 48. Thus, the standard iteration strategy can now be employed to find the remaining roots without just refinding the old ones. The only difficulty which is encountered by this process, is that the new function P can take on extremely large values if the root is small (close to zero). DRIVER then can call a separate subroutine SCALER which separates the power of ten of a number and carries it separately through the computation in DRIVER so that overflow within the computer does not occur.

6. FUNCTION SUBPROGRAMS FE and FI

These two subroutines return the value of a block transfer or response function to MAIN. In the case of some elements this is a trivially simple calculation. In cases where some surface operation is required, FE and FI prepare the call to CONVOL. The initial sections of FE and FI are computed GO TO's which take control to the proper subsection for the particular device class as determined by ITABLE(J,1). The listings for these routines are given in Figure 49 and Figure 50.

The COMMENT cards in the listing indicate the device class treated therein. Generally rather simple expressions have been used in our work so far. Note that in sections 7 and 8, s variable transfer functions are given for linear elements. The basic computational method can equally well be applied in the s variable domain.

7. FUNCTION SUBPROGRAM FEPHI(J,IRRAD)

FEPHI returns to MAIN the radiation voltage response as calculated by CONVOL; the listing of FEPHI is given in Figure 51. The prime task performed by FEPHI is to ascertain the correct surface number LSURF knowing only the block number J. First J is used as a look-up entry in ITABLE to find the device class number. This number, set to INDEX, is used together with the variable IRRAD coming in through the call, to find LSURF by look-up in the small table KSURF. IRRAD has the value one for X-ray and the value two for neutron irradiation. The contents

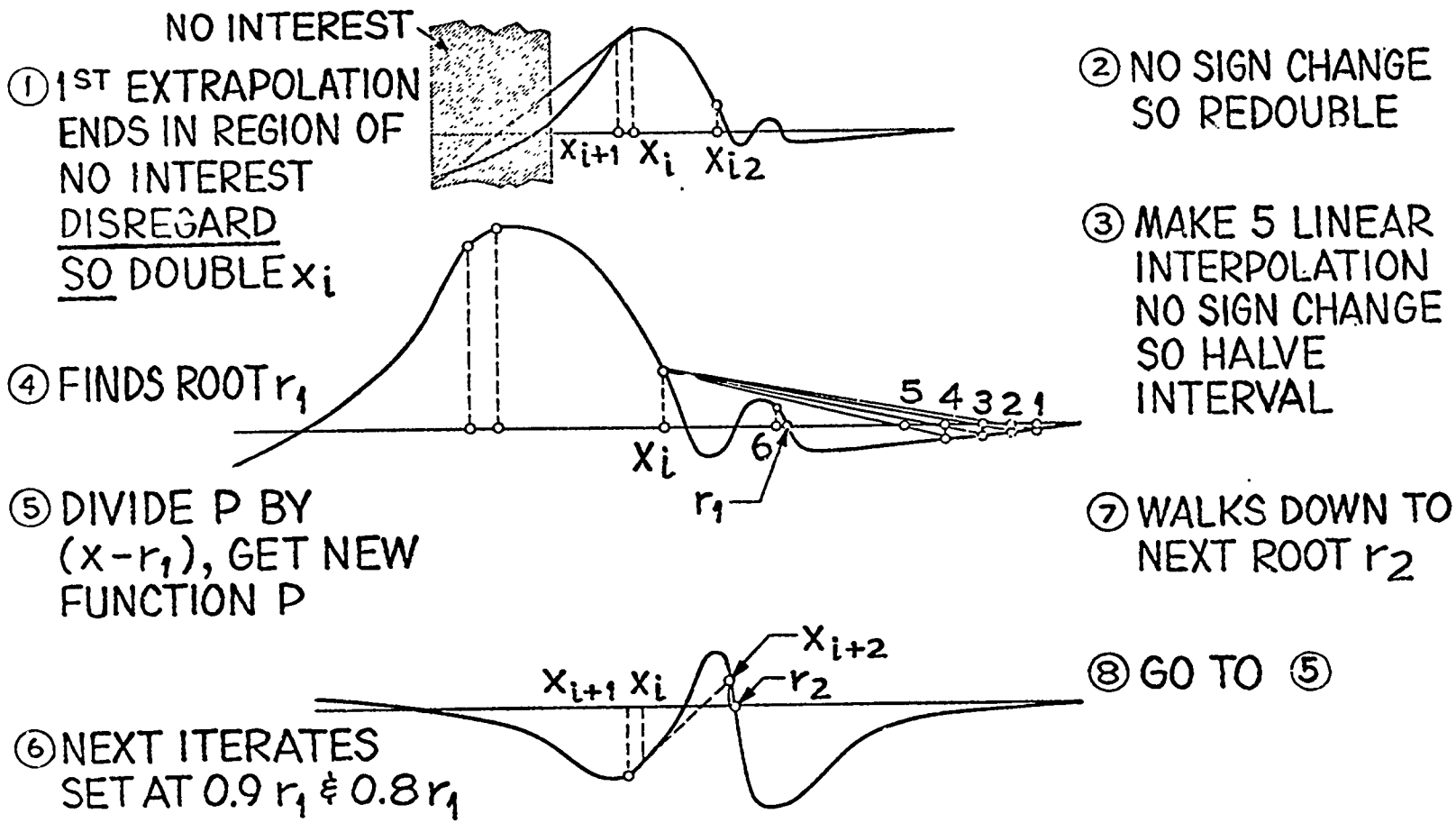


Figure 48. Strategies Employed in Linear Interpolation Root Finding Routine D R I V E R

```
.@ ELT FE,1,720302, 47804 , 1

000001                    FUNCTION FE(J)
000002                   INCLUDE SAP,LIST
000003                   DATA IN/5/,IT/6/
000004                    INDEX = ITABLE(J,1)
000005                    GO TO(1,2,3,4,5,6,7,8,9,10,11,12,13,14) , INDEX
000006                1   FE = FEE01(J)
000007                    RETURN
000008                2   FE = FEE02(J)
000009                    RETURN
000010                3   FE = FFE03(J)
000011                    RETURN
000012                4   FE = FEE04(J)
000013                    RETURN
000014                5   FE = FEE05(J)
000015                    RETURN
000016                6   FE = FEE06(J)
000017                    RETURN
000018                7   FE = FEE07(J)
000019                    RETURN
000020                8   FE = FEE08(J)
000021                    RETURN
000022                9   FE = FEE09(J)
000023                    RETURN
000024               10   FE = FEE10(J)
000025                    RETURN
000026               11   FE = FEE11(J)
000027                    RETURN
000028               12   FE = FEE12(J)
000029                    RETURN
000030               13 FE = FEE13(J)
000031                  RETURN
000032               14 FE = FEE14(J)
000033                  RETURN
000034          C
000035          C      01 = RESISTOR, SERIES CONFIGURATION.
000036                 FUNCTION FEE01(J)
000037                 GO TO (10,20), KROSS
000038               10 FEE01 = 1. - CIN(J,1)*R(J)/VIN(J,1)
000039                  RETURN
000040               20 FEE01 = VIN(J,1)/CIN(J,1) - R(J)
000041                  RETURN
000042          C
000043          C      02 = RESISTOR, SHUNT CONFIGURATION.
000044                 FUNCTION FEE02(J)
000045                 GO TO (10,20), KROSS
000046               10 FEE02 = 1.
000047                  RETURN
000048               20 FEE02 = VIN(J,1)/CIN(J,1)
000049                  RETURN
000050          C
000051          C      03 = DIODE, SERIES, FORWARD BIASED.
000052                 FUNCTION FEE03(J)
000053                 ARG = CIN(J,1)/CDIODE + 1.0
000054                 IF(ARG)  10,10,20
000055               10 FEE03 = 1.0 - (TKQ/VIN(J,1))*(ARG - 1.0)
000056                  RETURN
000057               20 FEE03 = 1.0 - (TKQ/VIN(J,1))*ALOG(ARG)
000058                  RETURN
```

Figure 49a. F E Listing

```
000059          C
000060          C     04 = DIODE, SERIES, REVERSE BIASED.
000061                FUNCTION FEE04(J)
000062                ARG = - CIN(J,1)/CDIODE + 1.0
000063                IF(ARG) 10,10,20
000064             10 FEE04 = (TKQ/VIN(J,1))*(ARG - 1.0)
000065                RETURN
000066             20 FEE04 = 1.0 + (TKQ/VIN(J,1)) * ALOG(ARG)
000067                RETURN
000068          C
000069          C     05 = DIODE, SHUNT, FORWARD BIASED.
000070                FUNCTION FEE05(J)
000071                FEE05 = 1.0
000072                RETURN
000073          C
000074          C     06 = DIODE, SHUNT, REVERSE BIASED.
000075                FUNCTION FEE06(J)
000076                FEE06 = 1.0
000077                RETURN
000078          C
000079          C     07 = CAPACITOR, SERIES, S VARIABLE ANALYSIS.
000080                FUNCTION FEE07(J)
000081                CINTGL(J,1) = ENTGRL(DT,J,CIN,IX,JT,M) + CINTGL(J,3)
000082                FEE07 = 1.0 - CINTGL(J,1)/(C(J)*VIN(J,1))
000083                RETURN
000084          C
000085          C     08 = CAPACITOR, SHUNT, S VARIABLE ANALYSIS
000086                FUNCTION FEE08(J)
000087                FEE08 = 1.0
000088                RETURN
000089          C
000090          C     09 = INDUCTANCE, SERIES, S VARIABLE ANALYSIS.
000091                FUNCTION FEE09(J)
000092                CINDT1(J,1) = DIFFER(DT,J,CIN,IX,JT,M)
000093                FEE09 = 1.0 - (FL(J)/VIN(J,1))* CINDT1(J,1)
000094                RETURN
000095          C
000096          C     10 = INDUCTANCE, SHUNT, S VARIABLE ANALYSIS.
000097                FUNCTION FEE10(J)
000098                FEE10 = 1.0
000099                RETURN
000100          C
000101          C     11 = INTEGRATED CIRCUIT 709 LINEAR OP AMP.
000102                FUNCTION FEE11(J)
000103                DATA ROUT/0.1/
000104                LSURF = 1
000105                ISTEER = 1
000106                V = VIN(J,1)
000107                IF(V.EQ.0.0) V = 1.E-6
000108                FEE11 = CONVOL(J,LSURF,ISTEER) - VOUT(J,2) * ROUT/V
000109                RETURN
000110          C
000111          C     12 = FLIP-FLOP
000112                FUNCTION FEE12(J)
000113                FEE12 = 0.0
000114                RETURN
000115          C
000116          C     13 = INTEGRATED CIRCUIT 9704 DUAL NAND GATE
000117                FUNCTION FEE13(J)
000118                DATA LSURF/6/, ISTEER/1/
```

Figure 49b. F E Listing (cont.)

```
000119                V = VIN(J,1)
000120                IF(V.EQ.0.0) V = 1.E-6
000121                IF(ITERAT.EQ.1.OR.V.NE.VOLD) X =  CONVOL(J,LSURF,ISTEER)
000122                FEE13 = X
000123                VOLD = V
000124                GO TO(10,20), KROSS
000125             10 RETURN
000126             20 FEE13 = FEE13 * V/CIN(J,1)
000127                RETURN
000128          C
000129          C     14 = INTEGRATED CIRCUIT 741 LINEAR OP AMP
000130                FUNCTION FEE14(J)
000131                DATA RIN/500.0/,ROUT/0.1/
000132                LSURF = 3
000133                ISTEER = 1
000134                V = VIN(J,1)
000135                IF(V.EQ.0.0) V = 1.E-6
000136                IF(ITERAT.EQ.1.OR.V.NE.VOLD) X = -CONVOL(J,LSURF,ISTEER)
000137                FEE14 = X - (COUT(J,1)+CIN(J,1)-V/RIN)*ROUT/V
000138                VOLD = V
000139                GO TO (10,20), KROSS
000140             10 RETURN
000141             20 FEE14 = FEE14 * V/CIN(J,1)
000142                RETURN
000143                END
```

Figure 49c. F E Listing (cont.)

```
P ELT FI,1,720302, 47807 , 1

000001                    FUNCTION FI(J)
000002                   INCLUDE SAP,LIST
000003                   INDEX = ITABLE(J,1)
000004                     GO TO(1,2,3,4,5,6,7,8,9,10,11,12,13,11), INDEX
000005                1    FI = FII01(J)
000006                     RETURN
000007                2    FI = FII02(J)
000008                     RETURN
000009                3    FI = FII03(J)
000010                     RETURN
000011                4    FI = FII04(J)
000012                     RETURN
000013                5    FI = FII05(J)
000014                     RETURN
000015                6    FI = FII06(J)
000016                     RETURN
000017                7    FI = FII07(J)
000018                     RETURN
000019                8    FI = FII08(J)
000020                     RETURN
000021                9    FI = FII09(J)
000022                     RETURN
000023               10    FI = FII10(J)
000024                     RETURN
000025               11    FI = FII11(J)
000026                     RETURN
000027               12    FI = FII12(J)
000028                     RETURN
000029               13 FI = FII13(J)
000030                  RETURN
000031          C
000032          C      01 = RESISTOR, SERIES CONFIGURATION.
000033                 FUNCTION FII01(J)
000034                 GO TO (10,20), KROSS
000035               10 FII01 = 1.
000036                  RETURN
000037               20 FII01 = CIN(J,1)/VIN(J,1)
000038                  RETURN
000039          C
000040          C      02 = RESISTOR, SHUNT CONFIGURATION.
000041                 FUNCTION FII02(J)
000042                 GO TO (10,20), KROSS
000043               10 FII02 = 1. - VIN(J,1)/(CIN(J,1)*R(J))
000044                  RETURN
000045               20 FII02 = CIN(J,1)/VIN(J,1) - 1.0/R(J)
000046                  RETURN
000047          C
000048          C      03 = DIODE, SERIES, FORWARD BIASED.
000049                 FUNCTION FII03(J)
000050                 FII03 = 1.0
000051                 RETURN
000052          C
000053          C      04 = DIODE, SERIES, REVERSE BIASED.
000054                 FUNCTION FII04(J)
000055                 FII04 = 1.0
000056                 RETURN
000057          C
000058          C      05 = DIODE, SHUNT, FORWARD BIASED.
```

Figure 50a. F I Listing

```
000059                FUNCTION FII05(J)
000060                IF(VIN(J,1)/TKQ-40.0)  20,10,10
000061             10 VIN(J,1)=TKQ * 12.0 *ALOG(ABS(CIN(J,1)*(1.0E-12)/CDIODE))
000062                GO TO 50
000063             20 IF(VIN(J,1))30,40,50
000064             30 FII05 = 1.0 - VIN(J,1)/(CIN(J,1) * RPDIOD)
000065                RETURN
000066             40 FII05 = 1.0
000067                RETURN
000068             50 FII05 = 1.0 -(CDIODE/CIN(J,1))*(EXP(VIN(J,1)/TKQ) - 1.0)
000069                RETURN
000070          C
000071          C     06 = DIODE, SHUNT, REVERSE BIASED.
000072                FUNCTION FII06(J)
000073                FII06 = 1.0 - (CDIODE/CIN(J,1))*(EXP(-VIN(J,1)/TKQ) - 1.0)
000074                RETURN
000075          C
000076          C     07 = CAPACITOR, SERIES, S VARIABLE ANALYSIS.
000077                FUNCTION FII07(J)
000078                FII07 = 1.0
000079                RETURN
000080          C
000081          C     08 = CAPACITOR, SHUNT, S VARIABLE ANALYSIS.
000082                FUNCTION FII08(J)
000083                VINDT1(J,1) = DIFFER(DT,J,VIN,IX,JT,M)
000084                FII08 = 1.0 - C(J)/CIN(J,1) * VINDT1(J,1)
000085                RETURN
000086          C
000087          C     09 = INDUCTANCE, SERIES,S VARIABLE ANALYSIS.
000088                FUNCTION FII09(J)
000089                FII09 = 1.0
000090                RETURN
000091          C
000092          C     10 = INDUCTANCE, SHUNT, S VARIABLE ANALYSIS.
000093                FUNCTION FII10(J)
000094                VINTGL(J,1) = ENTGRL(DT,J,VIN,IX,JT,M) + VINTGL(J,3)
000095                FII10 = 1.0 - VINTGL(J,1)/(FL(J)*CIN(J,1))
000096                RETURN
000097          C
000098          C
000099          C     11 = INTEGRATED CIRCUIT 709 LINEAR OP AMP.
000100                FUNCTION FII11(J)
000101                DATA RIN/500.0/, CGAIN/1.E+4/
000102                CUROUT = CGAIN*(CIN(J,1) -VIN(J,1)/
000103               1 RIN) + VOUT(J,1)/R(J+1)
000104                GO TO (10,20), KROSS
000105             10 FII11 = CUROUT/CIN(J,1)
000106                RETURN
000107             20 FII11 = CUROUT/VIN(J,1)
000108                RETURN
000109          C
000110          C
000111          C     12 = FLIP-FLOP
000112                FUNCTION FII12(J,
000113                GO TO(10,20), KROSS
000114             10 FII12 = 1.0+VOUT(J,2)/(CIN(J,1)*R(J+1))
000115                RETURN
000116             20 FII12 = (CIN(J,1)+VOUT(J,2)/R(J+1))/VIN(J,1)
000117                RETURN
000118          C
```

Figure 50b. F I Listing (cont.)

```
000119          C     13 = 9704 DUAL NAND GATE
000120                FUNCTION FII13(J)
000121                DATA CGAIN/1.E+4/
000122                CUROUT = CGAIN * CIN(J,1) + VOUT(J,1)/R(J+1)
000123                GO TO (10,20), KROSS
000124             10 FII13 = CUROUT/CIN(J,1)
000125                RETURN
000126             20 FII13 = CUROUT/VIN(J,1)
000127                RETURN
000128                  END
```

Figure 50c. F I Listing (cont.)

```
      @ ELT FEPHI,1,720302, 47805     , 1

000001                FUNCTION FEPHI(J,IRRAD)
000002                INCLUDE SAP,LIST
000003                INDEX = ITABLE(J,1)
000004                LSURF = KSURF(INDEX,IRRAD+3)
000005                IF(LSURF) 10,10,20
000006             10 FEPHI = 0.0
000007                RETURN
000008             20 ISTEER = IRRAD + 2
000009                FEPHI = CONVOL(J,LSURF,ISTEER)
000010                RETURN
000011                END
```

Figure 51. F E P H I Listing

of the array KSURF are shown in Table II. The columns of the array represent the type of transfer function surface upon which SURFB will have to perform an interpolation. Column one denotes the total number of surfaces available for a given device class. The rows of KSURF denote the device class as indexed by ITABLE, and corresponds to the sequence as indicated by comment cards in FE. The subprogram FIPHI is similar to FEPHI, with the column index variable increased by two compared to that in FEPHI so as to pick out the proper columns in KSURF.

8. FUNCTION SUBPROGRAM CONVOL(J,LSURF,ISTEER)

Superposition or convolution of the running sums created by the partitions driving back along the surface is the main operation performed by CONVOL. The listing of CONVOL is given in Figure 52. The variable J in the call is the block number. LSURF is the surface number being dealt with, and is passed on by CONVOL to TSURF. ISTEER tells CONVOL what type of stimulus function applies-- that is either voltage, current, X-ray dosage, or neutron dosage, and takes on values from one to four, respectively.

On the first time step, CONVOL calculates the length of the running sums needed by taking and dividing the length of the surface in the time direction by the initial time step. If this number is larger than the number of storage locations LMAX set aside for the running sums, a message is printed. The first time that CONVOL is called on a given time step from any of the routines which can call it, the section of program starting at statement 90 is entered. The DO loop limits are calculated using the time step counter M as moduloed down within the range LMAX, together with the IRANGE variable calculated earlier. The running sums move along in a fixed storage length and then fold back when the maximum is reached, as indicated by the COMMENT cards in the listing of Figure 52b.

With the limits on the DO established, the running sum is convolved. Four essential pieces of information are needed:

1. TIMER which is the elapsed time since a partition was created, until the current time step. The second column in the TIMER array contains that value in log form. TIMER is a look-up variable for surface interpolation.

Table II. KSURF Array

entries = 0 if blank

I \ J	1	2	3	4	5	6	7
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11	2	1	2				
12							
13	5	6		8	9	10	11
14	3	3		4	5		
15							
16							
17							
18							
19							
20							
	No. of surf. for given block type	TE	TI or STOR	TEPHIX	TEPHIN	TIPHIX	TIPHIN

I TABLE J, 1

```
@ ELT CONVOL,1,720302, 47797    , 1
000001                FUNCTION CONVOL(J,LSURF,ISTEER)
000002                INCLUDE SAP,LIST
000003                INCLUDE TIME,LIST
000004                INCLUDE XYZ,LIST
000005                COMMON/PARALL/LITER,JPARL
000006                DIMENSION U(LMAX,IX),SUMOLD(IX),TERM(IX),IRANGE(IX)
000007                DIMENSION KSURFX(12)
000008                LOGICAL NOMORE,KONVOL,IBOTH,IPRINT
000009                DATA (KSURFX(I),I=1,12)/1,1,1,2,2,1,0,1,2,1,2,0/
000010                DATA IT/6/
000011          C
000012          C     LMAX = FIRST DIMENSION IN U ARRAY.
000013          C
000014          C     THE KSURFX ARRAY INDICATES WHETHER THE XAXIS OF THE SURFACE IS
000015          C     LINEAR OR LOGARITHMIC. 1 = LINEAR, 2 = LOG.
000016          C
000017                IPRINT = .TRUE.
000018                MNEW = M
000019                IF(MNEW.NE.MOLD) MMOD10 = ((M/10)*10)/M
000020          C
000021          C     SELECTING THE PROPER STIMULUS VARIABLE.
000022                GO TO (2,3,4,5), ISTEER
000023              2 DRIVE = VIN(J,1)
000024                GO TO 10
000025              3 DRIVE = CIN(J,1)
000026                GO TO 10
000027              4 DRIVE = PHIXL
000028                GO TO 10
000029              5 DRIVE = PHINL
000030          C
000031          C     HERE THE TAG SUBSCRIPT FOR A SPECIFIC ONE OF A SPECIFIC DEVICE
000032          C     TYPE IS ESTABLISHED.
000033          C
000034             10 INDEX = ITABLE(J,1)
000035                KOUNT = 0
000036                DO  20  KK = 2, IS
000037                KS = KSURF(INDEX,KK)
000038                IF(KS.GT.0) KOUNT = KOUNT + 1
000039                IF(LSURF.NE.KS) GO TO 20
000040                JJ = ITABLE(J,2) - KSURF(INDEX,1) + KOUNT
000041                GO TO 22
000042             20 CONTINUE
000043             22 LL = KSURFX(LSURF)
000044          C
000045                IGO = 1
000046                IF((ISTEER.EQ.3.AND..NOT.KONVOL(1)).OR.(ISTEER.EQ.4.AND..NOT.
000047               1 KONVOL(2))) IGO = 2
000048                IF(ITERAT.GT.1.OR.IGO.EQ.2) GO TO 400
000049                IF(JPARL.EQ.1.AND.LITER.GT.1) GO TO 400
000050                IF(M-1)  30,30,90
000051             30 XHS =ABS( XHIGH(LSURF)/SCALE(LSURF,1))
000052                IF(MODE.EQ.1.AND.LL.EQ.1)  IRANGE(J) = XHS/DT
000053                IF(MODE.EQ.1.AND.LL.EQ.2)  IRANGE(J) = (10.**XHS)/DT
000054                IF(MODE.EQ.2.AND.LL.EQ.1)  IRANGE(J) = (ALOG10(XHS))/DLOGT
000055                IF(MODE.EQ.2.AND.LL.EQ.2)  IRANGE(J) = XHS/DLOGT
000056                IF(IRANGE(J).LT.20) IRANGE(J)=20
000057                WRITE(IT,40) J, IRANGE(J)
000058             40 FORMAT(/ 5X,8H IRANGE(,I2,3H) =,I4 /)
```

Figure 52a. C O N V O L Listing

```
000059              60 IF(IRANGE(J).LE.LMAX) GO TO 75
000060                 WRITE(IT,70)
000061              70 FORMAT(//49H TIME STEP DT TOO SMALL. WILL OVERFLOW U ARRAYS.   //)
000062                 IRANGE(J) = LMAX
000063              75 DO  80  J1 = 1, IX
000064                 SUMOLD(J1) = 0.0
000065              80 TERM(J1) = 0.0
000066                 GO TO 400
000067           C
000068           C ***************************************************************************
000069           C *
000070           C *   FOLDING OF ARRAYS
000071           C *
000072           C * 1. AT START
000073           C *
000074           C *   ILO1              IHI1                                          LMAX
000075           C *    1----------------I                                             I
000076           C *                   LATEST
000077           C *
000078           C * 2.LATER
000079           C *           ILO1             IRANGE(J)                IHI1          LMAX
000080           C *    1       I-------------------*-------------------I             I
000081           C *            OLDEST                                LATEST
000082           C *
000083           C * 3. STILL LATER
000084           C *   ILO1              IHI1                        ILO2              IHI2
000085           C *    1----------------I                          I-----------------I
000086           C *                  LATEST                       OLDEST           LMAX
000087           C *
000088           C ***************************************************************************
000089           C
000090              90 ILO1 = MPRIME - IRANGE(J)
000091                 IF(ILO1.LT.1) ILO1 = 1
000092                 IF(MPRIME.EQ.1) ILO1 = LMAX - IRANGE(J) + 1
000093                 TERM(JJ) = 0.0
000094                 IHI1 = MPRIME - 1
000095                 IF(IHI1.LT.1) IHI1 = LMAX
000096                 IF(MPRIME.LE.IRANGE(J).AND.IHI1.LT.IRANGE(J).AND.MODULO.GT.0)
000097                1 GO TO 100
000098                 NOMORE = .TRUE.
000099                 GO TO 200
000100             100 NOMORE =.FALSE.
000101                 ILO2 = MPRIME + LMAX - IRANGE(J)
000102                 IHI2 = LMAX
000103           C
000104             200 SUM = 0.0
000105           C
000106           C     SETTING DO LOOP LIMITS FOR SUMMING LOWER PART OF RANGE.
000107                 ILOW = ILO1
000108                 IHIGH = IHI1
000109                 IBOTH = .FALSE.
000110                 GO TO 220
000111           C
000112           C     SETTING DO LOOP LIMITS FOR SUMMING UPPER PART OF RANGE.
000113             210 ILOW = ILO2
000114                 IHIGH = IHI2
000115                 IBOTH = .TRUE.
000116           C
000117             220 IF(MMOD10.EQ.1.AND.IPRINT) WRITE(IT,222) M,MPRIME,ILOW,IHIGH,LSURF
000118             222 FORMAT(/  5H  M =,I3,11H,  MPRIME =,I3, 8H  ILOW =,I3,9H  IHIGH =,
```

Figure 52b. C O N V O L Listing (cont.)

```
000119              1 I3, 9H  LSURF =, I2,
000120              2    //2X, 64H L     TIMER       UIN         DTL         TEMP        SUM
000121              3     TSURF    )
000122            C
000123            CONVOLVING THE RUNNING SUMS BY DRIVING THE PARTITIONS ALONG THE SURFACE.
000124                  DO  300  L = ILOW, IHIGH
000125                  UIN = U(L,JJ)
000126                  IF(UIN) 230, 300, 230
000127              230 TIMER = TL(L,LL)
000128                  TSURFF = TSURF(TIMER,UIN,3,LSURF,LL)
000129                  UMULT = UIN
000130                  IF(LSURF.EQ.6) UMULT = 1.0
000131                  TEMP = TSURFF * UMULT * DTL(L,LL)
000132                  IF(MMOD10.EQ.1.AND.IPRINT) WRITE(IT,260) L,TIMER,UIN,DTL(L,LL),
000133                 1 TEMP,SUM,TSURFF
000134              260 FORMAT(2X,I3,1X,6(G10.3,1X))
000135                  SUM = SUM + TEMP
000136                  IF(TIMER.GT.XHIGH(LSURF).AND..NOT.ABS(TEMP).GT.EPSLON) U(L,JJ)=0.0
000137              300 CONTINUE
000138                  IF(.NOT.NOMORE.AND..NOT.IBOTH) GO TO 210
000139                  SUMOLD(JJ) = SUM
000140            C
000141            COMPUTING CONTRIBUTION OF PRESENT TIME STEP TO RESPONSE SUM.
000142            C
000143              400 IF(ITERAT.GT.1.AND.IGO.EQ.2) GO TO 480
000144                  U(MPRIME,JJ) = DRIVE
000145                  UIN = DRIVE
000146                  UMULT = UIN
000147                  IF(LSURF.EQ.6) UMULT = 1.0
000148                  SUM = SUMOLD(JJ) - TERM(JJ)
000149                  GO TO(430,440), MODE
000150              430 TIMER = DT
000151                  GO TO 460
000152              440 GO TO (450,470), IGO
000153              450 TIMER = DLOGT
000154              460 TERM(JJ) = UMULT * TSURF(TIMER,UIN,1,LSURF,LL)
000155                  SUMOLD(JJ) = SUM + TERM(JJ)
000156                  GO TO 480
000157              470 TIMER = TRADLG
000158                  IF(LL.NE.2) TIMER = 10.**TRADLG
000159                  SUMOLD(JJ) = UMULT * TSURF(TIMER,UIN,1,LSURF,LL)
000160              480 SUM = SUMOLD(JJ)
000161            C
000162              500 IF(DRIVE.EQ.0) DRIVE = 1.E-6
000163                  CONVOL = SUM/DRIVE
000164                  MOLD = M
000165                  RETURN
000166                  END
```

Figure 52c. C O N V O L Listing (cont.)

2. UMULT is the stimulus value at the time the partition was created. For the case of the 9704 voltage surface, UMULT = 1 since the surface is a response rather than transfer function surface. UMULT is also a look-up variable for surface interpolation.

3. DTL is the time step interval that existed at the time steps being swept over by the running sum as the partition moves along the surface. The second column in the array is the logarithm of the value.

4. TSURFF is the properly scaled value of the surface z coordinate returned from SURFB by TSURF using TIMER as the x look-up variable and UMULT for the y look-up variable.

The contribution of a particular partition to the sum is the product

$$TEMP = TSURFF * UMULT * DTL(L,LL)$$

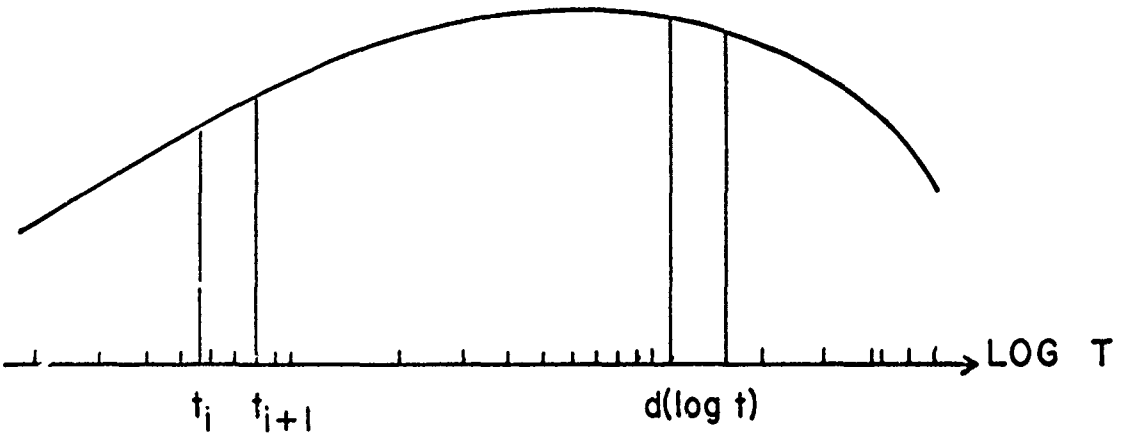
Every tenth time step during execution the running sums are printed for examination of the convolution process. When a particular term decreases below some value EPSLON, the multiplier UMULT is set zero for that term, so that the term is bypassed on subsequent summations.

The last section of CONVOL handles the contribution of the current time step to the total sum. Since the iteration process only affects this one term, after the first iteration pass only this section of CONVOL need be executed. The call which CONVOL sets up to TSURF is somewhat different here in that the call list contains a one rather than a three. This retrieves the z value of the surface rather than $\partial z/\partial x$, hence multiplication by DTL is not required. In the statement after 500, the value of the function CONVOL is computed as SUM/DRIVE, which casts the result into the sense of a transfer function, for use by FE et al.

One subtlety involved in CONVOL is the use of a doubly subscripted array for DTL which is dimensioned two in the second index, LL. LL indicates whether the time base is linear or logarithmic, taking the values one and two, respectively. If the surface time base is linear, then the linear DTL is required, whereas if

the basic mode of representation of the surface is logarithmic, then the time step

$$\text{TERM} = \text{UIN} \left.\frac{\partial T_u}{\partial \log t}\right|_{\text{UIN}(t_i),\, t-t_i} d(\log t_i)$$



Sketch Showing Equi-interval Convolution on a Log(time) Base

DTL must also be logarithmic since SURFB is returning $\partial z/\partial(\log t)$, rather than $\partial z/\partial t$. The setting of LL is done at the beginning of CONVOL by looking up the mode of the x axis of the surface in the array KSURFX.

9. FUNCTION SUBPROGRAM TSURF(TT,UU,II,L,LL)

TSURF is a relatively short program which interfaces CONVOL and SURFB, performing the task of rescaling the input and output information for internal compatibility. For example, the voltage transfer function surface of the 741, the vacuum cleaner, used milliseconds for the time axis and millivolts for the input voltage axis, while the SAP program uses nanoseconds for the time unit, and volts for the voltage unit. So TSURF multiplies the variable supplied by CONVOL, TT and UU, by SCALE for the surface number L, to obtain the proper values for use by SURFB.

TSURF finds the proper pointers for the X, Y, and Z arrays by look-up in the IPONTR array for the surface L. These pointers are set in the SURFB call to provide entry points in the array sequence because these same arrays are dimensioned differently in SURFB than in TSURF and MAIN. For example, Z is singly dimensioned

in the XYZ COMMON block, whereas it is triply dimensioned in SURFB.

Another major task performed by TSURF is decision making when the inputted look-up variables lie outside the domain of the surface. The actions taken have been kept simple, as can be seen by inspection of the listing of TSURF given in Figure 53.

The variable II selects the appropriate term in the ZA array returned by SURFB. For II = 1, ZA(1) = z, while for II = 3, ZA(3) = $\partial z/\partial x$.

10. FUNCTION SUBPROGRAM DAMAGE (J,IRRAD)

The routine DAMAGE is called by MAIN to calculate the permanent degradation of the device due to radiation exposure. A rather simple technique has been used which makes use of the 741 radiation voltage transfer function due to neutrons, TPHIVN. The isochronal cross-section occurring at t = 875 ms is used as the x axis look-up variable in a call to TSURF. This isochronal is approximately the same as that given in Figure 24b, bottom.

The accumulated dose is integrated by DAMAGE, as shown in the listing of Figure 54, using simple trapezoidal integration. The integrated dose is used as the y axis look-up variable for TSURF. Thus the surface interpolation returns the value of TPHIVN at the accumulated dose point along the isochronal. This is then divided by the lowest dose value of the function, TPHINO, to provide the ratio by which the maximum output has decreased. MAIN then uses this ratio, in the transfer function sense, to degrade the device output as calculated in the normal manner with electrical and radiation transient responses superimposed.

The variable J in the call list is the block number, and IRRAD indicates the irradiation type, one corresponding to Xrays, and two to neutrons. However, the same surface is used for the damage function (as a temporary expedient).

11. SUBROUTINE PARLEL(N,LBLOCK,LMAX,FACTOR,CNOUT,VNOUT,VNIN,KPRINT,JPARAL)

This routine handles the parallel iteration algorithm, and its listing is given in Figure 55. The items in the call list represent the following:

- N is the input node number,
- LBLOCK is an array which contains the block numbers for a given parallel sequence,

```
@ ELT TSURF,1,720304, 74057    , 1

000001                FUNCTION TSURF(TT,UU,II,L,LL)
000002                INCLUDE XYZ,LIST
000003                DIMENSION ZA(8)
000004                LOGICAL ISYM
000005                DATA XHI6/250./
000006                DATA IT/6/
000007                FACTOR = 1.0
000008                T = TT * SCALF(L,1)
000009                U = UU * SCALF(L,2)
000010                IF(T.LT.XLOW(L)) GO TO 200
000011                XHI = XHIGH(L)
000012                IF(L.EQ.6) XHI = XHI6
000013                IF(T.GT.10.*XHI) GO TO 200
000014                IF(T.GT.XHI) T = XHI
000015                IF(U.LT.YLOW(L).AND.ISYM(L)) U = -U
000016                IF(U.LT.YLOW(L).AND..NOT.ISYM(L)) U = YLOW(L)
000017                IF(U.GT.YHIGH(L)) GO TO 300
000018            100 IP = IPONTR(L,1)
000019                JP = IPONTR(L,2)
000020                KP = IPONTR(L,3)
000021                IF(IP.EQ.0.OR.JP.EQ.0.OR.KP.EQ.0) GO TO 400
000022                CALL SURFB(X(IP),IXDIM(L),Y(JP),IYDIM(L),Z(KP),T,U,ZA,L)
000023                TSURF = ZA(II)*SCALE(L,3)*FACTOR
000024                IF(II.EQ.3) TSURF = TSURF * SCALE(L,1)
000025                RETURN
000026            200 TSURF = 0.0
000027                RETURN
000028            300 FACTOR = YHIGH(L)/U
000029                U = YHIGH(L)
000030                GO TO 100
000031            400 WRITE(IT,410)
000032            410 FORMAT(120H1  TERMINATED BY TSURF SINCE POINTER FOR SURFB IS ZERO.
000033               1 ISURF DATA CARD IS IN ERROR AND A NEEDED SURFACE IS NOT READ IN.)
000034                CALL EXIT
000035                END
```

Figure 53. T S U R F Listing

```
@ ELT DAMAGE,1,720302, 47798    , 1

000001                FUNCTION DAMAGE(J,IRRAD)
000002            C   AS PRESENTLY SET UP THIS ROUTINE REQUIRES THAT THE TPHIVN SURFACE
000003            C   OF THE 741 BE READ IN AT EXECUTION TIME BY MAIN. LSURF = 5, ZVN741
000004                INCLUDE SAP,LIST
000005                INCLUDE TIME,LIST
000006                DATA TLOOK/5.75/,TPHIN0/1.32/,DOSEN/.001/,DOSEX/.001/
000007            C
000008                INDEX = ITABLE(J,1)
000009                IF(KSURF(INDEX,IRRAD+3).EQ.0) GO TO 300
000010            C
000011                T = TIME(MPRIME,1)
000012                IF (.NOT.(T.GT.TOLD)) GO TO 100
000013                DOSEN = DOSEN + DT*10.**PHINL
000014                DOSEX = DOSEX + DT*10.**PHIXL
000015                DOSENL = ALOG10(DOSEN)
000016                DOSEXL = ALOG10(DOSEX)
000017            C
000018              100 GO TO (120,140), IRRAD
000019              120 DAMAGE = DOSEXL * TSURF(TLOOK,DOSEXL,1,5,1)/TPHIN0
000020                  GO TO 200
000021              140 DAMAGE = DOSENL * TSURF(TLOOK,DOSENL,1,5,1)/TPHIN0
000022              200 TOLD = T
000023                  RETURN
000024              300 DAMAGE = 1.0
000025                  RETURN
000026                  END
```

Figure 54. D A M A G E Listing

```
      ⍟ ELT PARLEL,1,720302, 47809    , 1

000001                SUBROUTINE PARLEL(N,LBLOCK,LMAX,FACTOR,CNOUT,VNOUT,VNIN,CNIN,     PAR
000002               1 KPRINT,JPARAL)
000003          C
000004          C     DR. R. G. STEWART,  AREA CODE 415, 941-6699
000005          C     STEWART RESEARCH ENTERPRISES, 23376 BELVOIR DR., LOS ALTOS, CALIF.
000006          C
000007          C     PARLEL HANDLES BALANCING OF CURRENTS IN PARALLEL CONNECTED BLOCKS.
000008          C
000009                INCLUDE SAP,LIST
000010                COMMON/PARALL/LITER,JPARL
000011                DIMENSION LBLOCK(IX,IX),LMAX(IX),FACTOR(IX),CNOUT(IX),VNOUT(IX)
000012               1          ,VNIN(IX),CNIN(IX),DELTAV(IX),JPARAL(IX),FEE(IX),FII(IX)
000013               2          ,FEOLD(IX),DUDI(IX),VAVRAG(IX)
000014                DATA IN/5/,IT/6/,KMOST/ 2/
000015                DATA VTEST/0.02/,CTEST/0.02/,LIMIT/ 4/
000016          C
000017          COMPUTING CURRENTS IN PARALLEL BRANCHES.
000018          C
000019                VTOTAL = VNIN(N)
000020                CTOTAL = CNIN(N)
000021                KSTATE = KROSS
000022                KROSS = 2
000023          C
000024          C
000025          C     K IS THE PARALLLEL ITERATION DO, L STEPS ALONG BRANCHES.
000026          C
000027                LHI = LMAX(N)
000028                DO  20  LL = 1, LHI
000029                LB = LBLOCK(N,LL)
000030             20 VIN(LB,1) = VTOTAL
000031          C
000032          C     ITERATING TO FIND NEW CURRENT FACTORS.
000033          C
000034                DO  100  K = 1, KMOST
000035                CSUM = 0.0
000036                LITER = K
000037                DO  30  LL = 1, LHI
000038                LB = LBLOCK(N,LL)
000039                CIN(LB,1) = CTOTAL * FACTOR(LB)
000040             30 CSUM = CSUM + CIN(LB,1)
000041          C
000042                FRACT = CSUM/CTOTAL
000043                DO  40  LL = 1, LHI
000044                LB = LBLOCK(N,LL)
000045             40 CIN(LB,1) = CIN(LB,1)/FRACT
000046          C
000047          C     NOW KIRCHOFFS CURRENT LAW IS SATISFIED AT INPUT NODE.
000048          C     NEXT PROPAGATE THRU BRANCHES TO FIND OUTPUT VOLTAGE USING
000049          C     CROSSED VOLTAGE TRANSFER FUNCTIONS.
000050          C
000051                VSUM = 0.0
000052                DO  60  LL = 1, LHI
000053                LB = LBLOCK(N,LL)
000054                JPARL = JPARAL(N)
000055                ITRSAV = ITERAT
000056                NITER = 0
000057          C
000058          C     SELF-CONSISTENCY ITERATION LOOP
```

Figure 55a. P A R L E L Listing

```
000059          C
000060             50 NITER = NITER + 1
000061                ITERAT = ITRSAV * NITER
000062                VOLD = VOUT(LB,1)
000063                COLD = COUT(LB,1)
000064                FEE(LB) = FE(LB)
000065                FII(LB) = FI(LB)
000066                VOUT(LB,1)=FEE(LB)*CIN(LB,1)
000067                COUT(LB,1)=FII(LB)*VIN(LB,1)
000068                TESTV = ABS(1.0-VOUT(LB,1)/VOLD)
000069                TESTC = ABS(1.0-COUT(LB,1)/COLD)
000070                IF(.NOT.(ABS(VOLD).GT.0.)) TESTV = 0.0
000071                IF(.NOT.(ABS(COLD).GT.0.)) TESTC = 0.0
000072                IF((TESTV.GT.VTEST.OR.TESTC.GT.CTEST).AND.NITER.LE.LIMIT) GO TO 50
000073                ITERAT=ITRSAV
000074          C
000075          C     CONSISTENCY ACHIEVED
000076          C
000077             60 VSUM = VSUM + VOUT(LB,1)
000078                VAVRAG(N) = VSUM/LMAX(N)
000079                IF(ABS(VAVRAG(N)).GT.15.0) VAVRAG(N) = 15.0 * ISIGN(1,VAVRAG(N))
000080                KOUNT = 0
000081          C
000082          C     FINDING NEW CURRENT SPLITTING FACTORS.
000083                DO  80  LL = 1, LHI
000084                LB = LBLOCK(N,LL)
000085                DELTAV(LB) = VOUT(LB,1)-VAVRAG(N)
000086                DUDI(LB) = (FEE(LB)-FEOLD(LB))/(CIN(LB,1)-CIN(LB,2))
000087                IF(K.EQ.1) DUDI(LB) = 0.0
000088                DELTAI = DELTAV(LB)/(FEE(LB) + CIN(LB,1)*DUDI(LB))
000089                FEOLD(LB) = FEE(LB)
000090                CIN(LB,2) = CIN(LB,1)
000091                FACTOR(LB) = (CIN(LB,1)-DELTAI)/CTOTAL
000092                IF(ABS(DELTAV(LB)) - 0.00001)  76, 76, 80
000093             76 KOUNT = KOUNT + 1
000094             80 CONTINUE
000095          C
000096                IF(KPRINT) 82,90,82
000097             82 DO  84  LL = 1, LHI
000098                LB = LBLOCK(N,LL)
000099             84 WRITE(IT,86) K,LB,DUDI(LB) ,CIN(LB,1),FEE(LB),FII(LB),DELTAV(LB)
000100               1,FACTOR(LB),VOUT(LB,1),COUT(LB,1)
000101             86 FORMAT(3H K=,I3,3H L=,I2,6H DUDI=,G9.4,5H CIN=,G9.4,5H FEE=,G9.4,
000102               15H FII=,G9.4,8H DELTAV=,G9.4,8H FACTOR=,G9.4,6H VOUT=,G9.4,6H COUT
000103               2=,G9.4)
000104                LB = LBLOCK(N,1)
000105                WRITE(IT,88) VAVRAG(N),CTOTAL,VIN(LB,1)
000106             88 FORMAT(10X,7HVAVRAG=,G9.4,8H CTOTAL=,G9.4,5H VIN=,G9.4)
000107          C
000108             90 IF(KOUNT - LMAX(N))  100, 200, 200
000109          COMPLETION OF ITERATION.
000110            100 CONTINUE
000111          C
000112          C
000113            200 CSUM = 0.0
000114                DO  220  LL = 1, LHI
000115                LB = LBLOCK(N,LL)
000116            220 CSUM = CSUM + COUT(LB,1)
000117                CNOUT(N) = CSUM
000118                VNOUT(N) = VAVRAG(N)


000119                KROSS = KSTATE
000120                JPARL = 0
000121                IF(KPRINT)  400, 300, 400
000122            300 RETURN
000123            400 WRITE(IT,410)K,N,CNOUT(N),N,VNOUT(N)
000124            410 FORMAT( 6H AFTER,I4,19H ITERATIONS  CNOUT(,I2,2H)=,G10.4,
000125               1 8H, VNOUT(,I2,2H)=,G10.4, /)
000126                RETURN
000127                END
```

Figure 55b. P A R L E L Listing (cont.)

- LMAX is the number of blocks in parallel in the sequence,
- FACTOR is the current splitting factor for a given block,
- CNOUT and VNOUT are the output voltages and currents returned to MAIN,
- VNIN and CNIN are the voltage and current at the input node as supplied by MAIN,
- KPRINT controls printing of the results of the parallel iteration, and
- JPARAL is an array created by SETUP which indicates whether a node requires the use of PARLEL; JPARAL = 1 implies yes.

The actions taken in PARLEL are indicated by the COMMENT cards in the listing of Figure 55. The input current is split into the blocks, and then propagated using the crossed voltage transfer functions. Since the Univac 1108 sets the result of dividing any number by zero equal to zero, logical IF tests set the variables TESTV and TESTC equal to zero if the denominators VOLD or COLD vanish. Otherwise the following consistency test would automatically drop through when it should not.

After self-consistency is attained, the new current splitting factors are calculated, the deviations from the floating average output voltage determined, and the iteration continued if the deviations exceed the test value. After the iteration loop is completed, the voltage and current at the output node are computed and returned to MAIN.

12. SUBROUTINE PLOTEM(KIND,VNIN,CNIN,VNOUT,CNOUT,NMAX,INITAL)

PLOTEM performs the tasks of reading plot title and control cards, and loading information into the plot arrays. The listing of PLOTEM is given in Figure 56. The entries in the call list perform the following tasks:

- KIND controls action taken - if negative, data cards are read; if zero, points are entered into plot arrays; if positive, PLOT6 is called to force plotting,
- VNIN, CNIN, VNOUT, and CNOUT are the arrays containing node voltages and currents as supplied by MAIN,
- NMAX is the final output node number,

```
@ ELT PLOTEM,1,720302, 47811    , 1
000001                  SUBROUTINE PLOTEM(KIND,VNIN,CNIN,VNOUT,CNOUT,NMAX,INITAL)
000002                  INCLUDE SAP,LIST
000003                  INCLUDE TIME,LIST
000004                  DIMENSION VNIN(IX),CNIN(IX),VNOUT(IX),CNOUT(IX)
000005                  PARAMETER IDIM=100,JDIM=6
000006                  DIMENSION X(IDIM,JDIM),Y(IDIM,JDIM),XX(IDIM,JDIM),YY(IDIM,JDIM)
000007                 1,LABEL7(48),ILABEL(6,8),IPOINT(7),TITLE(12),IORIGN(7),SKALE(7)
000008                 2,LAWG(7),NOXY(JDIM),IPAR(2)
000009                  LOGICAL INITAL
000010                  DIMENSION XSCALE(6),XSKALE(6),JPLOT(4),JIPLOT(4)
000011                  DATA (XSCALE(I),I=1,6)/6HLOG(II,6HNANOSE,6HMICROS,6HMILLIS,
000012                 16HSECOND,6H       /, (XSKALE(I),I=1,6)/1.,1.,1.E-3,1.E-6,1.E-9,1.0/
000013                  DATA ICURNT/1HI/,IVOLT/1HV/,IN/5/,IT/6/
000014                  DATA ICRAD/2HIR/,IVRAD/2HVR/
000015          C
000016              5 FORMAT(8X,12A6)
000017              6 FORMAT(A5,48A1,I3,3X,E12.5,3X,3X,I3)
000018              7 FORMAT(A1,4X,8A6,I3,3X,E12.5,6X,I3)
000019          C
000020                  IF(KIND) 200,400,800
000021          C
000022          CALLIN PLOT6 HERE WILL READ IN ONE DATA CARD. IF PLOTIT APPEARS IN THE
000023          C FIRST 6 COLUMNS, THEN  CALCOMP PLOT IS MADE. IF NOT, ONLY PRINTER
000024          C PLOTS. THE  PLOT  TAPE IS ALSO INITIALIZED IF REQUIRED.
000025          C
000026            200 IF(INITAL) CALL PLOT6(X,Y,NOXY,IPAR,IDIM,JDIM,-1,LABEL7,ILABEL
000027                1,IPOINT,TITLE,IORIGN,SKALE,LAWG,NUMBER,SIZE,IPAGE)
000028          C
000029          C     INITIALIZATION OF ROUTINE
000030                  INITAL =.FALSE.
000031          C
000032          C READING THE PLOT ASSIGNMENT CARD. THIS DETERMINES WHICH BLOCK OUTPUT
000033          C VOLTAGES OR CURRENTS ARE PLOTTED. VNIN(1) AND VNOUT(NMAX) ARE ALWAYS
000034          C PLOTTED. NUMJ IS THE NUMBER OF ADDITIONAL BLOCK VOLTAGES AND CURRENTS.
000035          C WHERE NUMJ.LE.4 .
000036          C
000037                  READ(IN,26) NUMJ,(JPLOT(I),JIPLOT(I),I=1,4),TSCALE
000038               26 FORMAT(I3,4(I3,A2),6X,A6)
000039                  WRITE(IT,28)NUMJ,(JPLOT(I),JIPLOT(I),I=1,4),TSCALE
000040               28 FORMAT(46H THE PLOT ASSIGNMENT CARD AS READ IN  SAYS...,/,I3,4(I3,
000041                 1A2),6X,A6  /)
000042                  NUMBER = NUMJ + 2
000043                  KARDS = 0
000044                  READ(IN,5) (TITLE(J),J=1,12)
000045                  WRITE(IT,5) (TITLE(J),J=1,12)
000046                  READ(IN,6) SIZE,(LABEL7(J),J=1,48),IORIGN(7),SKALE(7),LAWG(7)
000047                  READ(IN, 7)IPOINT(1),(ILABEL(1,J),J=1,8),IORIGN(1),SKALE(1),LAWG(1
000048                 1)
000049                  DO  30  I = 1,6
000050                  IF(XSCALE(I).NE.TSCALE) GO TO 30
000051                  XSC = XSKALE(I)
000052                  GO TO 32
000053               30 CONTINUE
000054                  XSC = 1.0
000055               32 DO  564  I = 2, NUMBER
000056              564 READ(IN, 7) IPOINT(I),(ILABEL(I,J),J=1,8),IORIGN(I),SKALE(I),
000057                 1 LAWG(I)
000058                  RETURN
```

Figure 56a. P L O T E M Listing

```
000059              400 IF(M - 1) 404, 404, 410
000060              404 NUMPTS = 0
000061                  NOPTS = 0
000062                  MODPTS = IFIX(MMAX/100) + 1
000063              410 NUMPTS = NUMPTS + 1
000064                  TIM = TIME(MPRIME,MODE) * XSC
000065                  DO  420  I = 1, NUMBER
000066              420 X(NUMPTS,I) = TIM
000067                  Y(NUMPTS,2) = VNIN(1)
000068                  Y(NUMPTS,1) = VNOUT(NMAX)
000069                  IF(NUMBER.LE.2) GO TO 500
000070                  DO  460  I = 1, NUMJ
000071                  II = JPLOT(I)
000072                  IF(JIPLOT(I).EQ.ICRAD)  Y(NUMPTS,I+2) =COUT(II,3)
000073                  IF(JIPLOT(I).EQ.IVRAD)  Y(NUMPTS,I+2) =VOUT(II,3)
000074                  IF(JIPLOT(I).EQ.ICURNT) Y(NUMPTS,I+2) = COUT(II,1)
000075                  IF(JIPLOT(I).EQ.IVOLT)  Y(NUMPTS,I+2) = VOUT(II,1)
000076              460 CONTINUE
000077              500 IF(MOD(NUMPTS,MODPTS))  560,520,560
000078              520 NOPTS = NOPTS + 1
000079                  DO  540  I = 1, NUMBER
000080              540 XX(NOPTS,I) = TIM
000081                  YY(NOPTS,2) = VNIN(1)
000082                  YY(NOPTS,1) = VNOUT(NMAX)
000083                  IF(NUMBER.LE.2) GO TO 560
000084                  DO  550  I = 1, NUMJ
000085                  II = JPLOT(I)
000086                  IF(JIPLOT(I).EQ.ICRAD)  YY( NOPTS,I+2)=COUT(II,3)
000087                  IF(JIPLOT(I).EQ.IVRAD)  YY( NOPTS,I+2)=VOUT(II,3)
000088                  IF(JIPLOT(I).EQ.ICURNT)  YY(NOPTS,I+2) = COUT(II,1)
000089                  IF(JIPLOT(I).EQ.IVOLT)   YY(NOPTS,I+2) = VOUT(II,1)
000090              550 CONTINUE
000091              560 IF(NUMPTS.NE.100.AND.KIND.EQ.0) RETURN
000092              570 DO  580  I = 1, NUMBER
000093              580 NOXY(I) = NUMPTS
000094                  CALL PCNT(IPAGE)
000095                  IPAGE = IPAGE +1
000096                  CALL PLOT6(X,Y,NOXY,IPAR,IDIM,JDIM,KARDS,LABEL7,ILABEL,IPOINT
000097                 1,TITLE,IORIGN,SKALE,LAWG,NUMBER,SIZE,IPAGE)
000098                  NUMPTS = 0
000099                  RETURN
000100              800 IF(KIND - 2) 810,820,900
000101              810 IF(NUMPTS.LT.3) RETURN
000102                  GO TO 570
000103              820 IF(MMAX.LT.103) RETURN
000104                  DO  840  I = 1, NUMBER
000105              840 NOXY(I) = NOPTS
000106                  CALL PCNT(IPAGE)
000107                  IPAGE = IPAGE + 1
000108                  CALL PLOT6(XX,YY,NOXY,IPAR,IDIM,JDIM,0,LABEL7,ILABEL,IPOINT
000109                 1,TITLE,IORIGN,SKALE,LAWG,NUMBER,SIZE,IPAGE)
000110                  NOPTS = 0
000111                  RETURN
000112              900 CALL PLOT6(X,Y,NOXY,IPAR,IDIM,JDIM,-2,LABEL7,ILABEL,IPOINT
000113                 1,TITLE,IORIGN,SKALE,LAWG,NUMBER,SIZE,IPAGE)
000114            C     THIS IS THE NORMAL TERMINATION OF THE ENTIRE SAP.
000115                  CALL EXIT
000116                  RETURN
000117                  END
```

Figure 56b. P L O T E M Listing (cont.)

- INITAL = .TRUE. causes PLOT6 to read one data card; if PLOTIT is contained in the first six columns, the plot tape is initialized, and machine plots will be made.

The FORMATS that read the plot title and control cards are numbers 5, 6, 7, 26, and 28. The COMMENT cards in the listing indicate the function of the plot assignment card. JPLOT is the block number whose output is to be plotted, JIPLOT indicates whether the voltage, current, radiation induced voltage, or the radiation induced current is to be plotted, being tested against the entities in the last two DATA cards in the listing. TSCALE sets the scale factor used on the time axis of the plots, since nanoseconds is not the best unit if time intervals measured in seconds are being treated. SKALE is tested against the spelling indicated in the first DATA card.

The normal values for the quantities read in by FORMATS 6 and 7 are: SIZE = SMALL, IORIGN = -1, SKALE = -1.0, LAWG = 0 . PLOT6 can make large or small printer plots. If two page printer plots are desired, set SIZE = LARGE. PLOT6 can plot up to six dependent variables versus one independent variable in one plot.

The final completion of a run occurs in PLOTEM with a CALL EXIT, after the call to PLOT6 with -2 in the seventh list position which causes proper plot tape termination.

SECTION VI

RESULTS COMPUTED BY SAP USING TRANSFER FUNCTION SURFACES

The concepts discussed in Section II, and the surface fitting techniques developed in Section IV, provide the tools needed to evaluate the usefulness of the nonlinear surface convolution method for simulating the effects of electrical and radiation stimuli on integrated circuits. The results presented in this section are new in the research sense. No prior efforts existed that treated the radiation effects on devices in this way. The results show that the ideas have promise in the sense of an approximation having an engineering level of precision. Further, the execution time on the Univac 1108 is reasonably low -- typically 23 seconds for 100 time steps. The core storage available on the 1108 of 65K decimal was sufficient to contain the SAP program, all the plot routines, and six surfaces without segmenting. If the plot routines had been segmented, since they are needed only at the end, at least ten or more additional surfaces could have been contained in core. Thus it appears that the method does indeed have sufficient computational characteristics to make genuine its usefulness for real applications.

1. 741 OP AMP - ELECTRICAL RESULTS

The computed results due to application of a 1.0 mv pulse to the 741 T_e surface, Figure 20, are shown in Figure 57. The input pulse is shown in Figure 57a, the input and output voltages and the output current in Figure 57b, and the details of the leading and trailing edges of the pulse in Figure 57c and d. The plot points on the plots occur at twice the interval of computation, otherwise no line could be seen. The number of time steps was 100. Because the input pulse waveform is almost a square pulse, the convolution process amounts to almost an isovoltage sampling of the surface in this case, except for two points on the rising and falling edges which move back at half the peak pulse level and sample the surface at the 500 microvolt portion.

To ascertain the sine wave response obtained with the T_e surface, six runs were made varying the frequency and the amplitude of the input waveform. These runs were made after the self-consistency loop had been inserted into MAIN, and the optimization of DRIVER's convergence tests was still under way. The frequencies were chosen

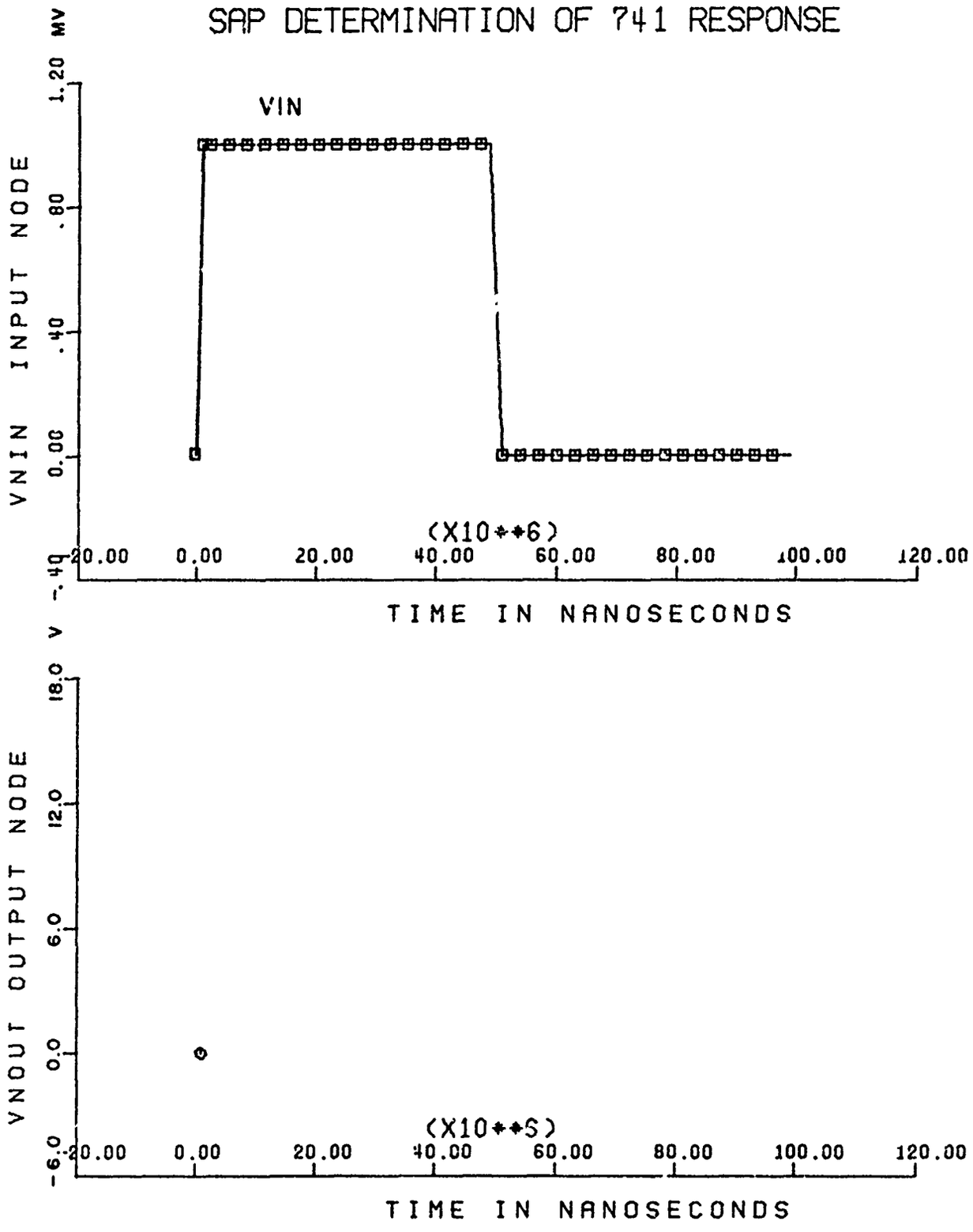


Figure 57a. 741 Op Amp Response to 50 ms Step Pulse.
Input Waveform has 1 ms Rise and Fall Times.
See Figure 57b for VNOUT waveform.

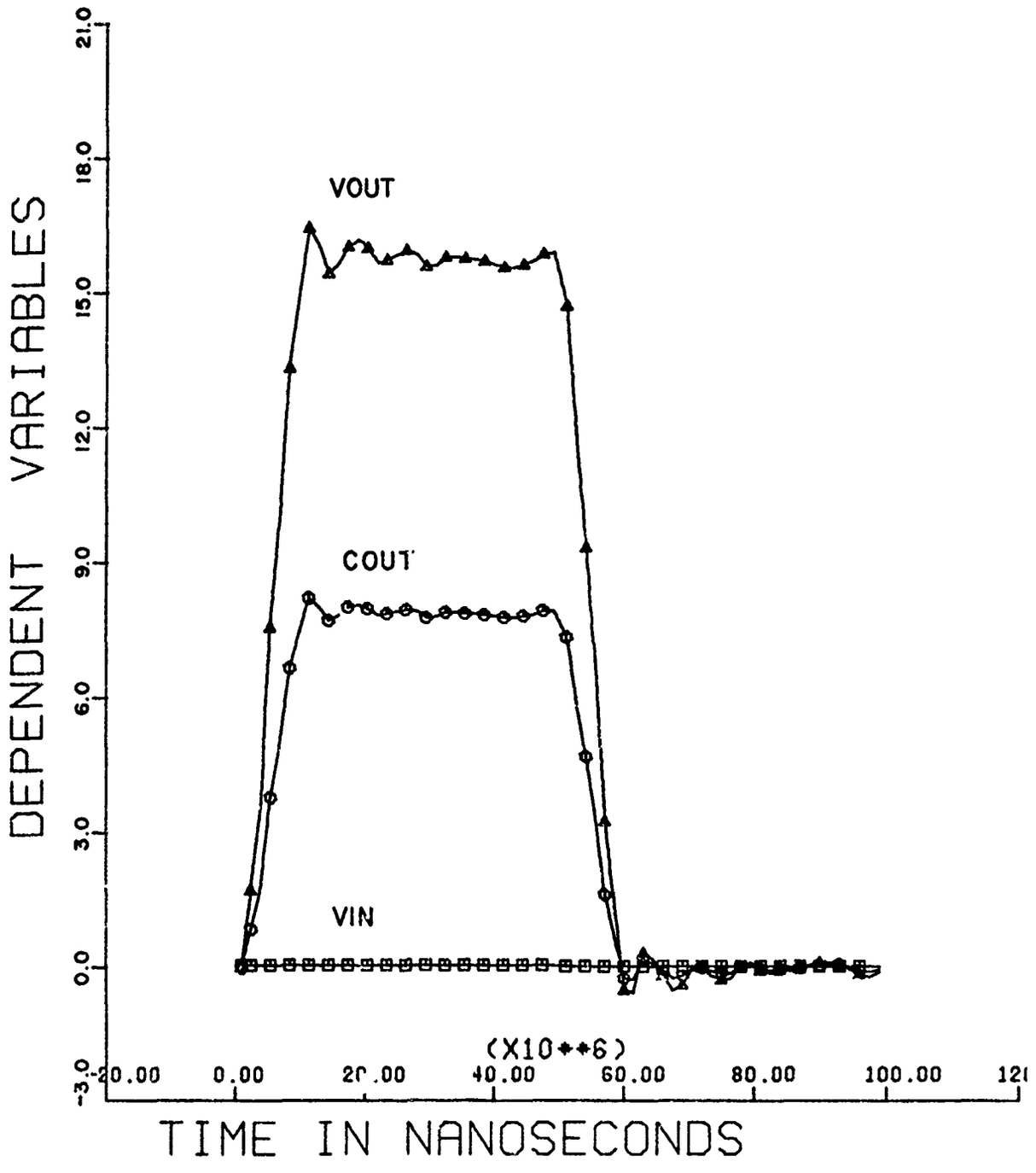


Figure 57b. 741 Op Amp Response to Step Pulse, VIN and VOUT in volts, COUT in ma.

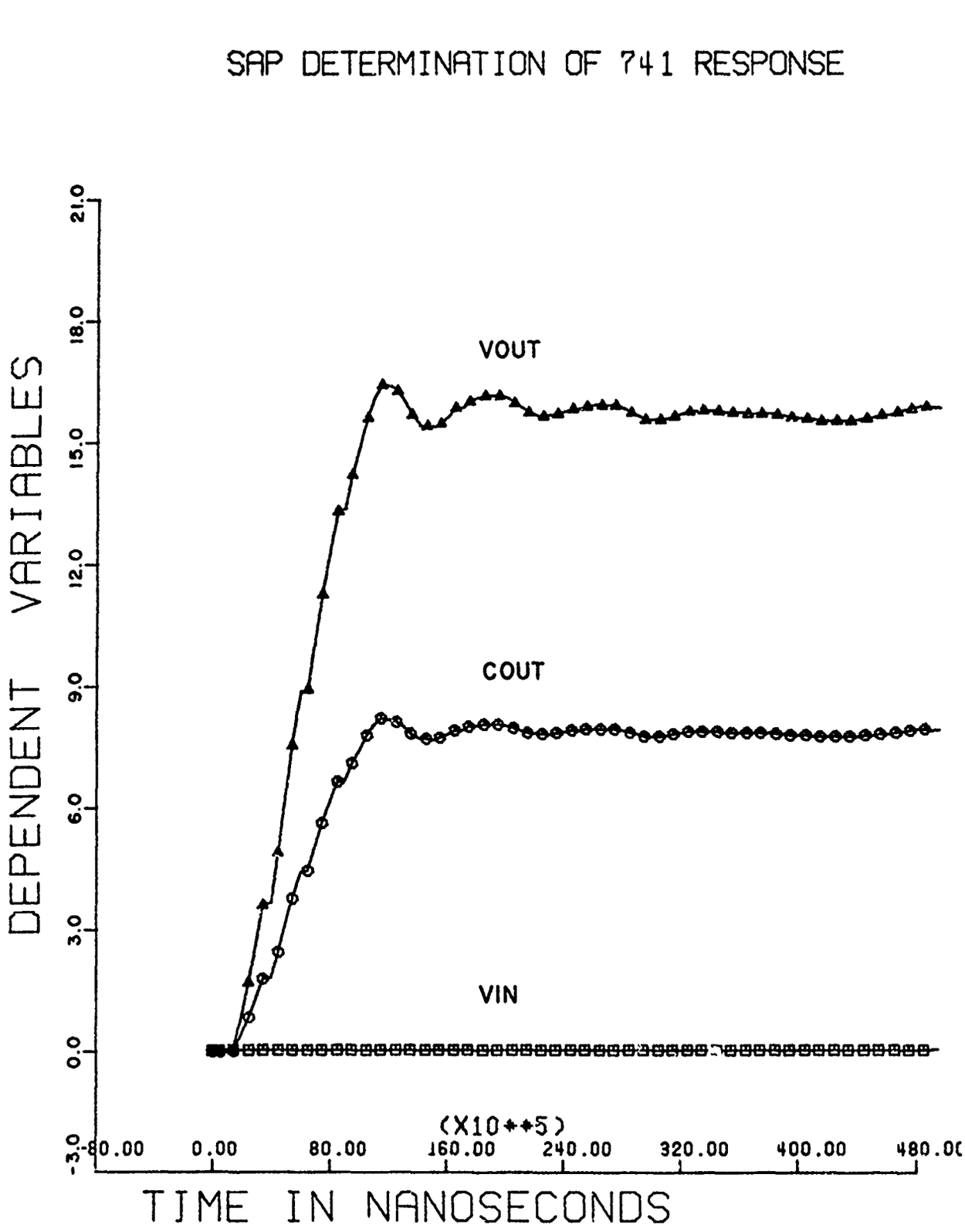


Figure 57c. 741 Op Amp Response to Step Pulse.
Leading Edge Portions of Waveforms.

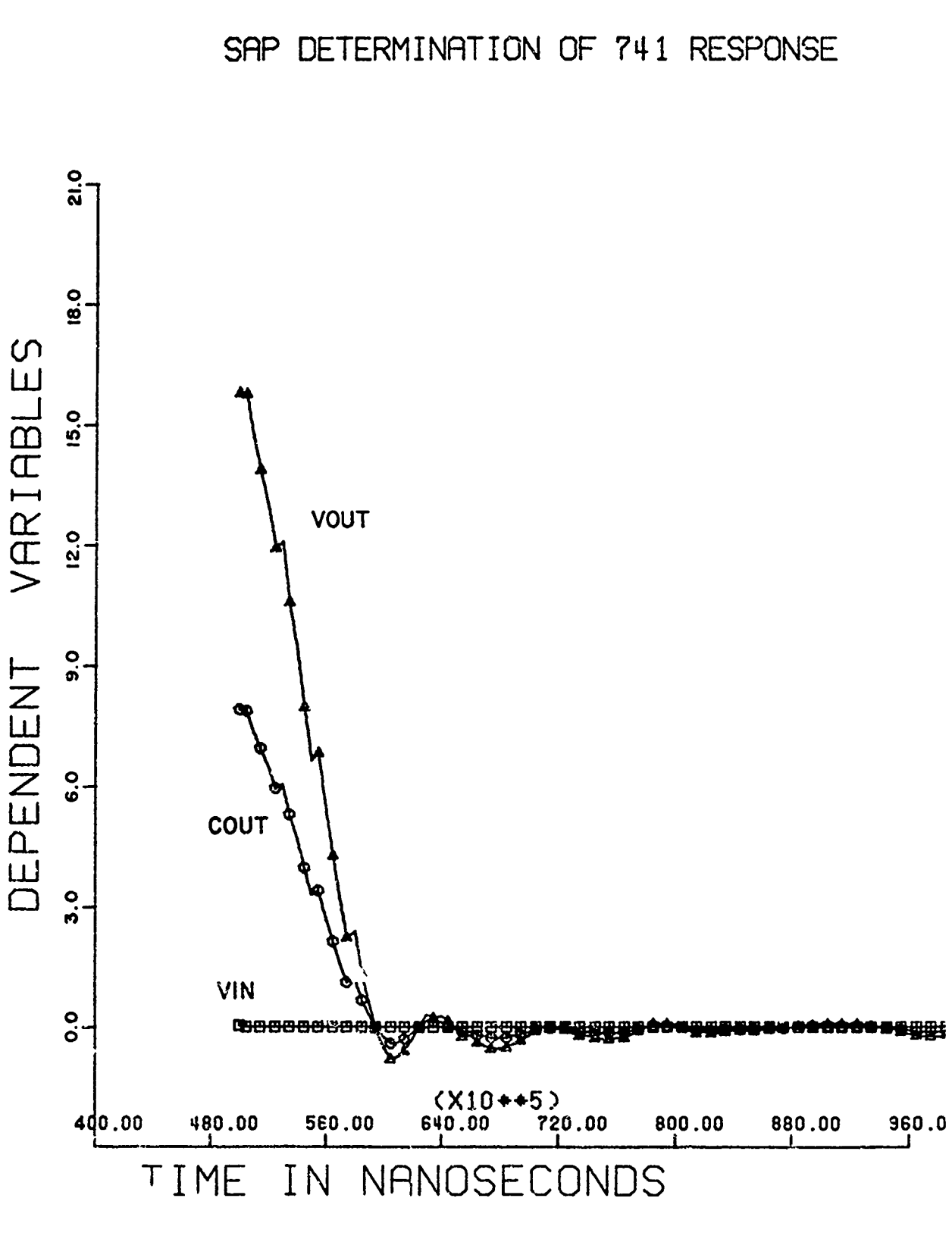


Figure 57d. 741 Op Amp Response to Step Pulse.
Trailing Edge Portions of Waveforms.

to be about an order of magnitude above, below, and approximately at the reciprocal of the open loop time constant. The peak input waveform amplitudes were chosen to lie in the linear and nonlinear operating regions. Since the stimulus is a sine wave, partitions are driven back along the surface at input voltages which range from plus to minus the peak amplitude of the sine wave. Thus a sine wave input reaching into the nonlinear region also samples the linear region of the device characteristic. This is the same situation as for a real device.

The machine plots of the six runs are contained in Figure 58. The summary of the conditions applying for the runs are:

Fig	Run	VIN	Phase	Freq	Comments
58a	335	0.2mv	0^{o}	2 Hz	
58b	336	2.0		2	Time step too large for surface.
58c	337	2.0	37^{o}	20	Lost iterate twice but came back in.
58d	338	0.2		20	
58e	340	0.2	78^{o}	200	Note correct form of transient.
58f	341	2.0		200	" " " " "
58g	349	2.0		200	Return of 341 with CONVOL bug corrected; note only slight effect on results.

The phase given is that of the output lagging the input. The change of the phase with frequency yields $f_{corner} \approx 20$ Hz. In the case of the 2 Hz runs, the step size was so large that only two partitions were sampling the surface at any moment of the calculation. Now since the effective time constant of the T_e surface for the 741 decreases with increased excitation (until slew rate is reached) that small a number of sampling partitions yields an unsatisfactory result as can be seen in Figure 58b, for the 2.0 mv nonlinear excitation level. Compare that with the result contained in Figure 58a for a linear excitation whose effective time constant is about an order of magnitude greater, and it is seen that a fairly smooth output function is computed for the same time step size.

The curve for the 2.0 mv, 20 Hz, run shown in Figure 58c is interesting in that it demonstrates an interesting aspect of convolutional calculation methods, namely at about 150 milliseconds the iteration process lost stability. Yet, in two time steps the iteration routine DRIVER regained stability with only a very small effect remaining from the prior iteration loss. This results from the fact that convolution is the superposition of many terms, and unless a faulty iteration yields an excessively large term, the large number of the good terms minimizes the effect of

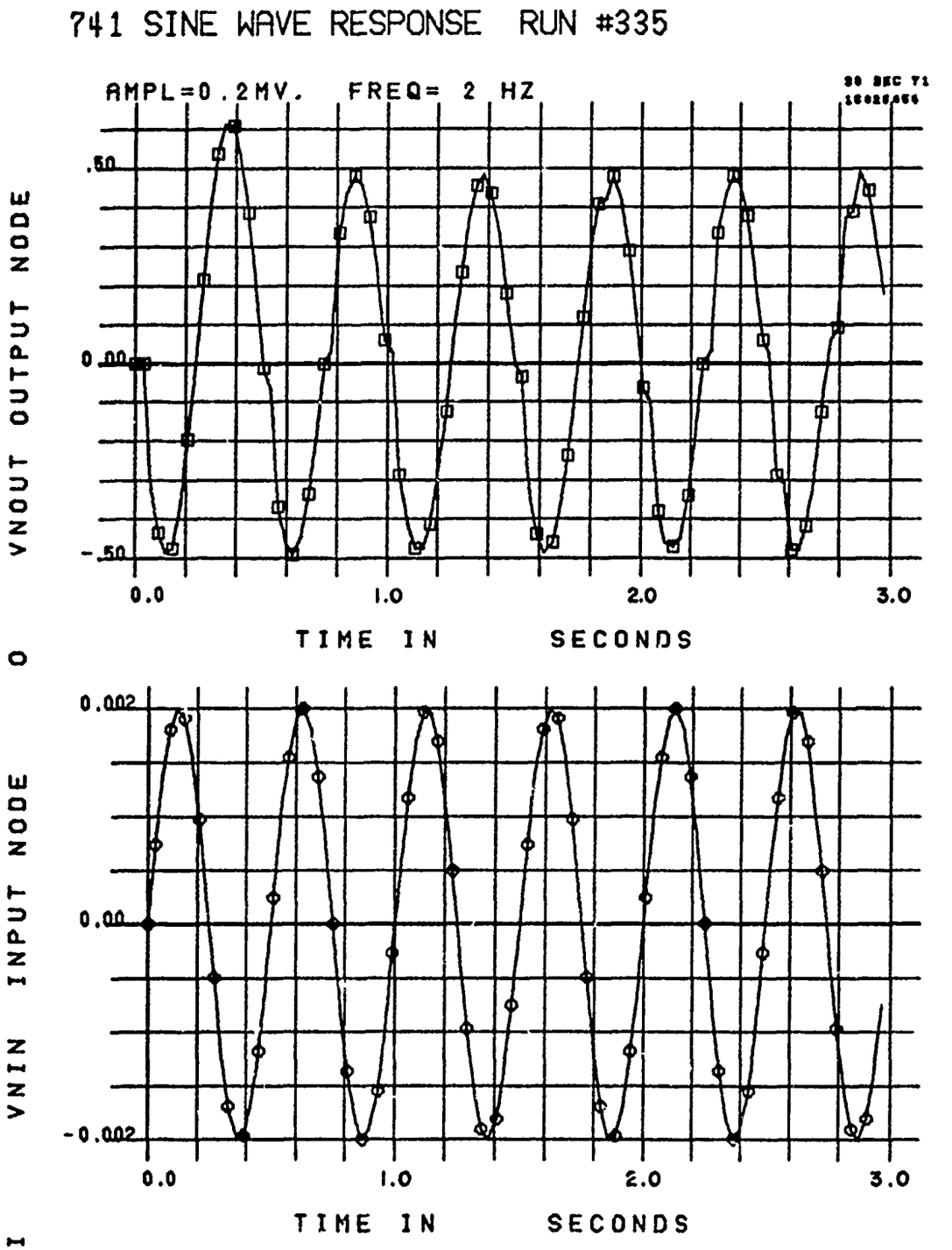


Figure 58a. 741 Response to 2 Hz Sine Wave, Op Amp Input Amplitude of 0.2 mv is One-Tenth Input Node Voltage, VNIN.

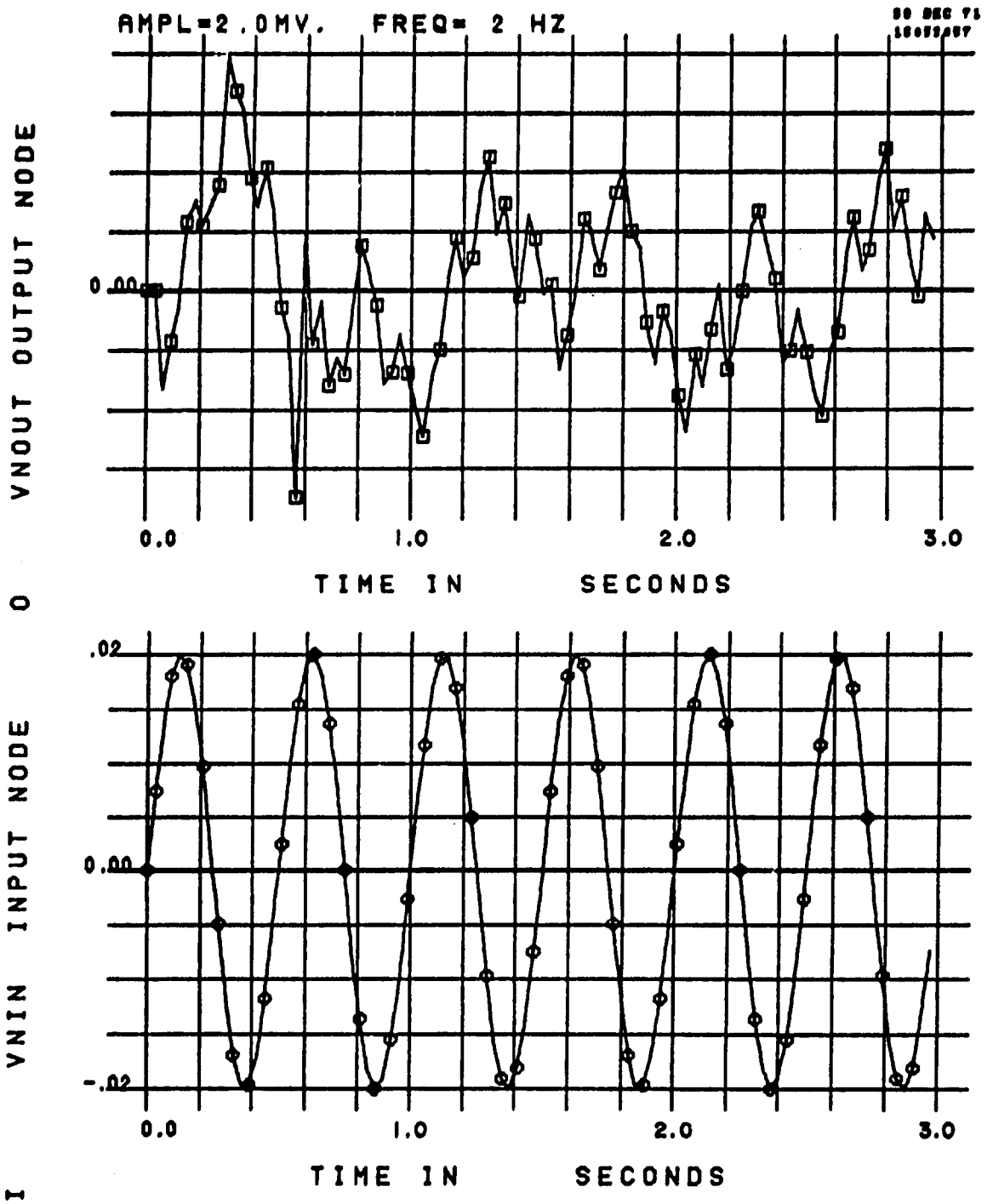


Figure 58b. 741 Response to 2 Hz, 2 mv Sine Wave

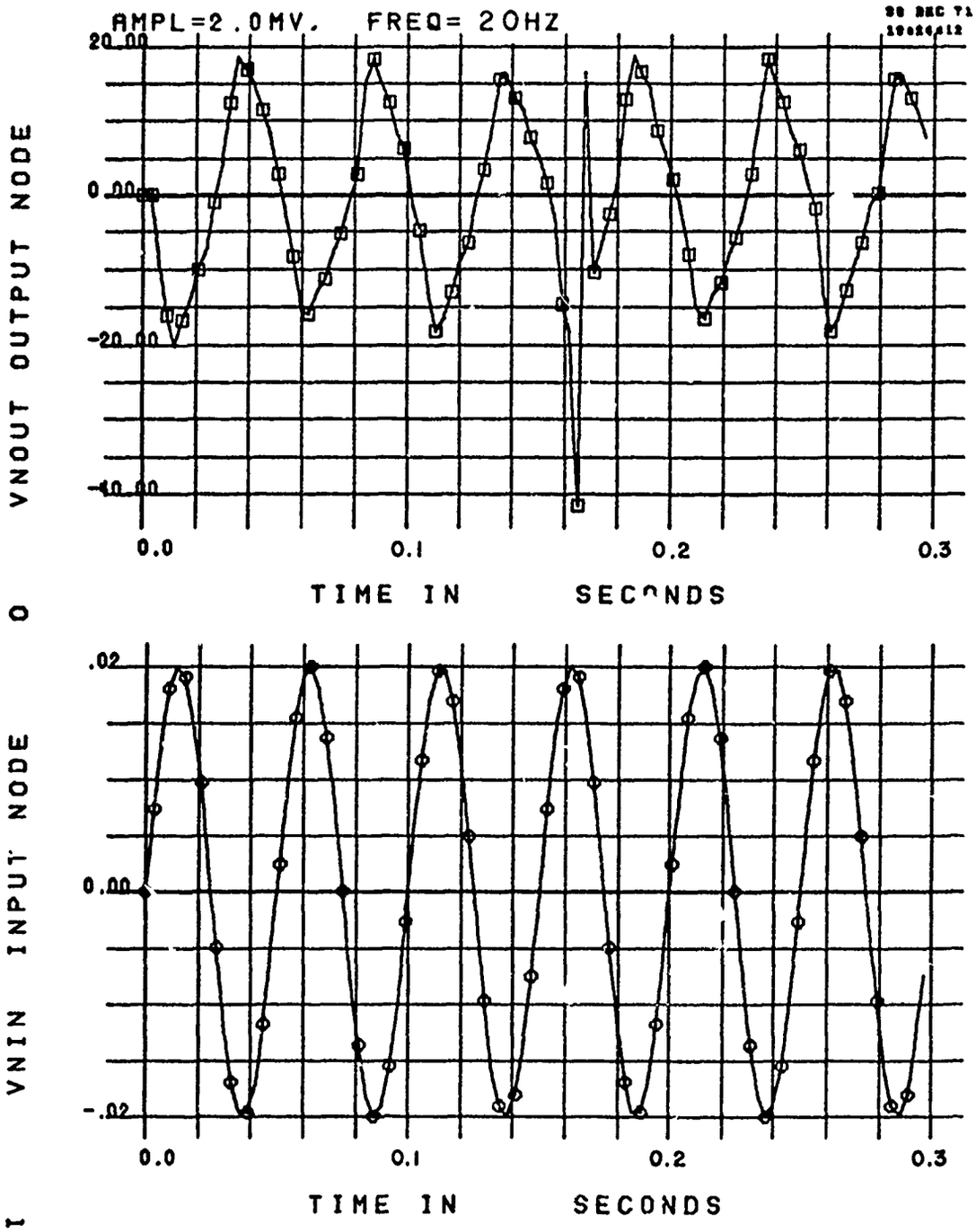


Figure 58c. 741 Response to 20 Hz, 2.0 mv Sine Wave

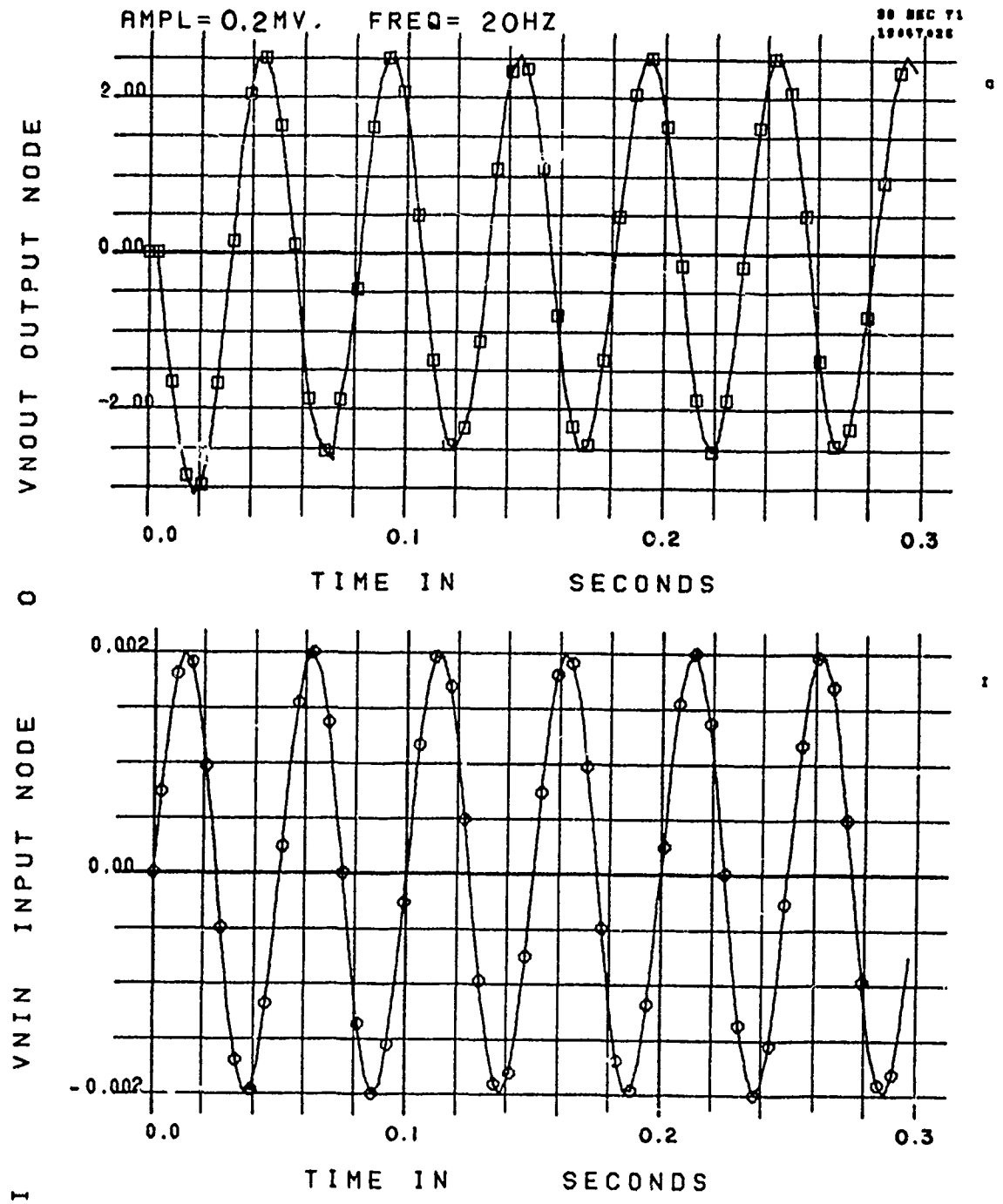


Figure 58d. 741 Response to 20 Hz, 0.2 mv Sine Wave

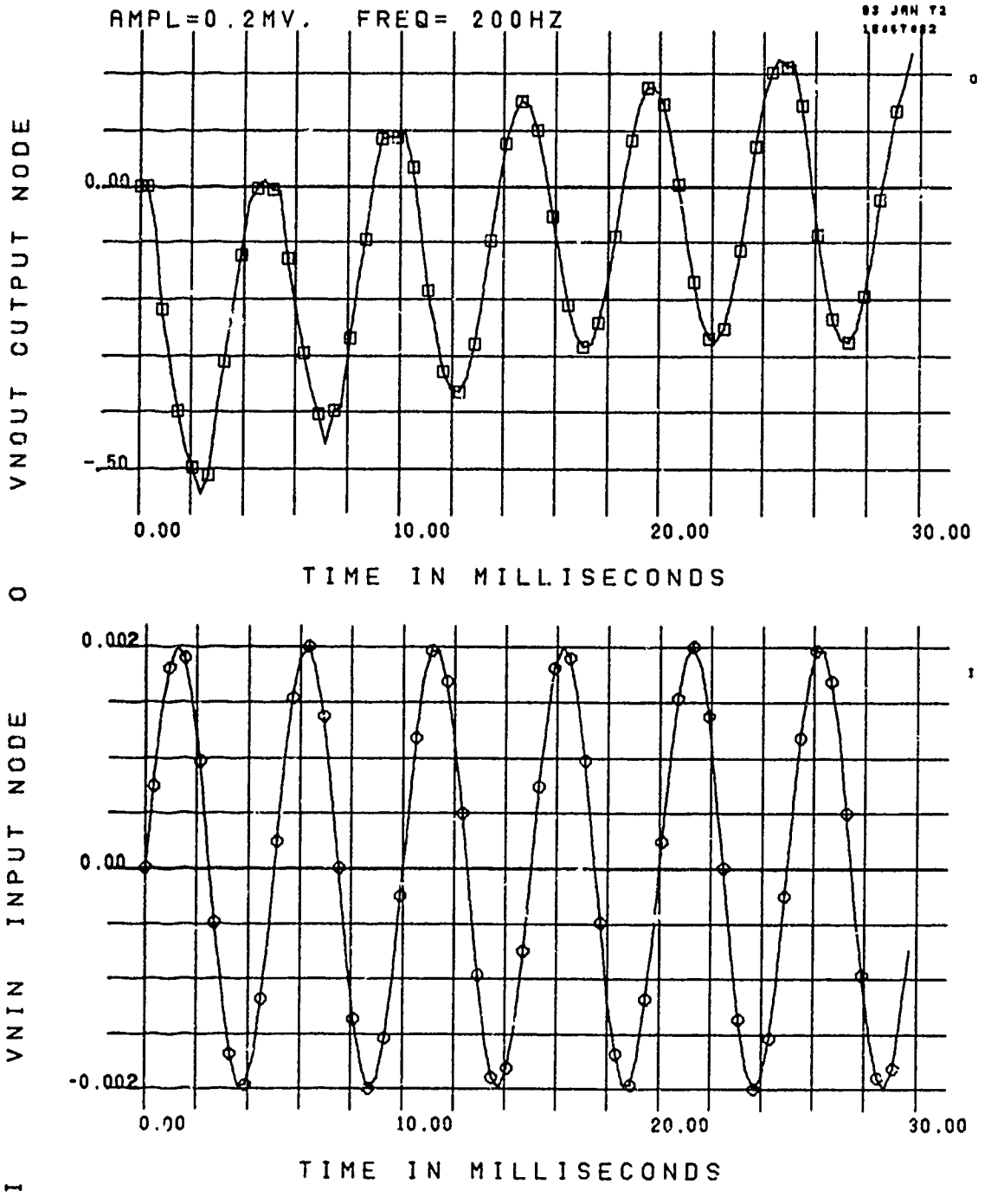


Figure 58e. 741 Response to 200 Hz, 0.2 mv Sine Wave

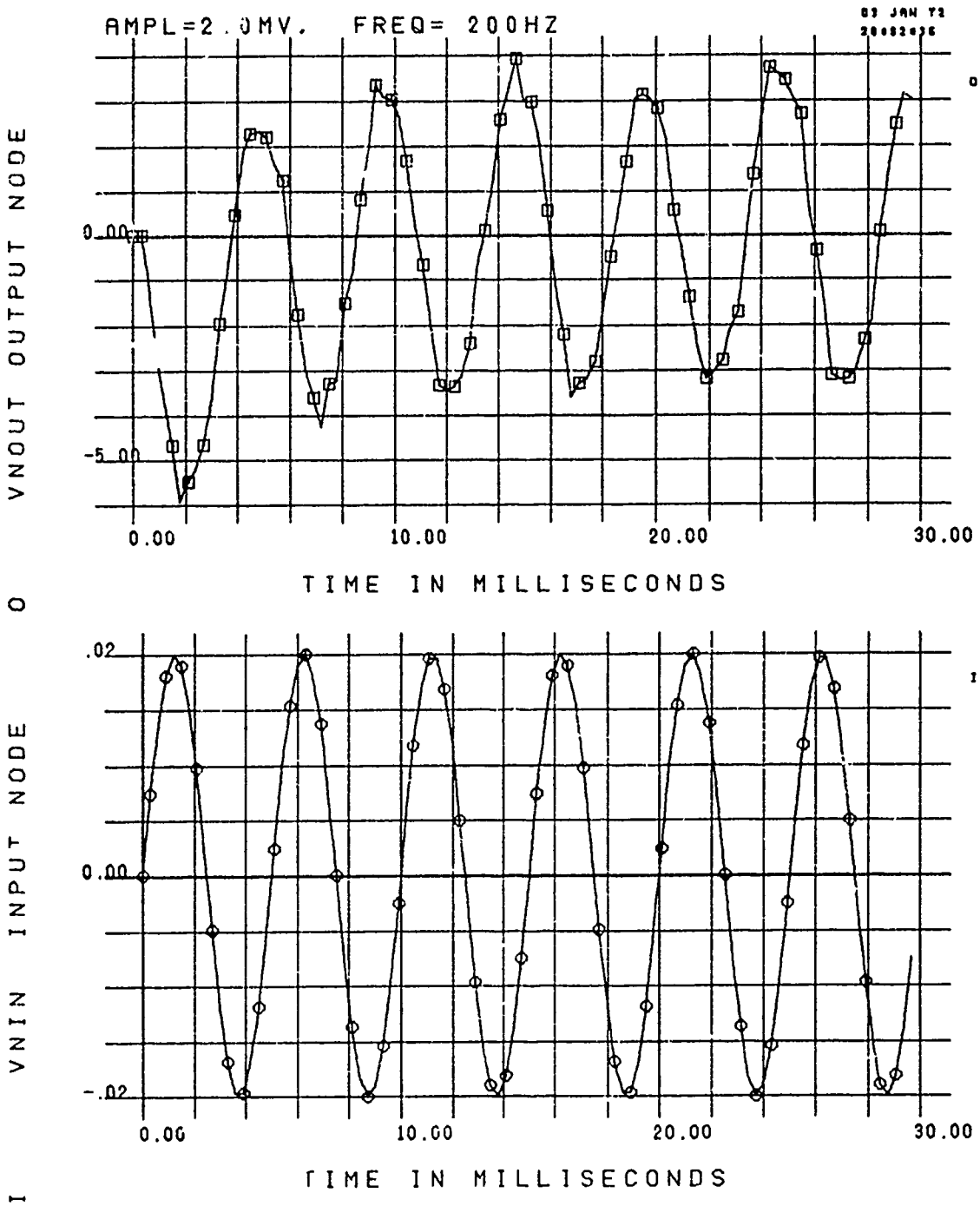


Figure 58f. 741 Response to 200 Hz, 2.0 mv Sine Wave

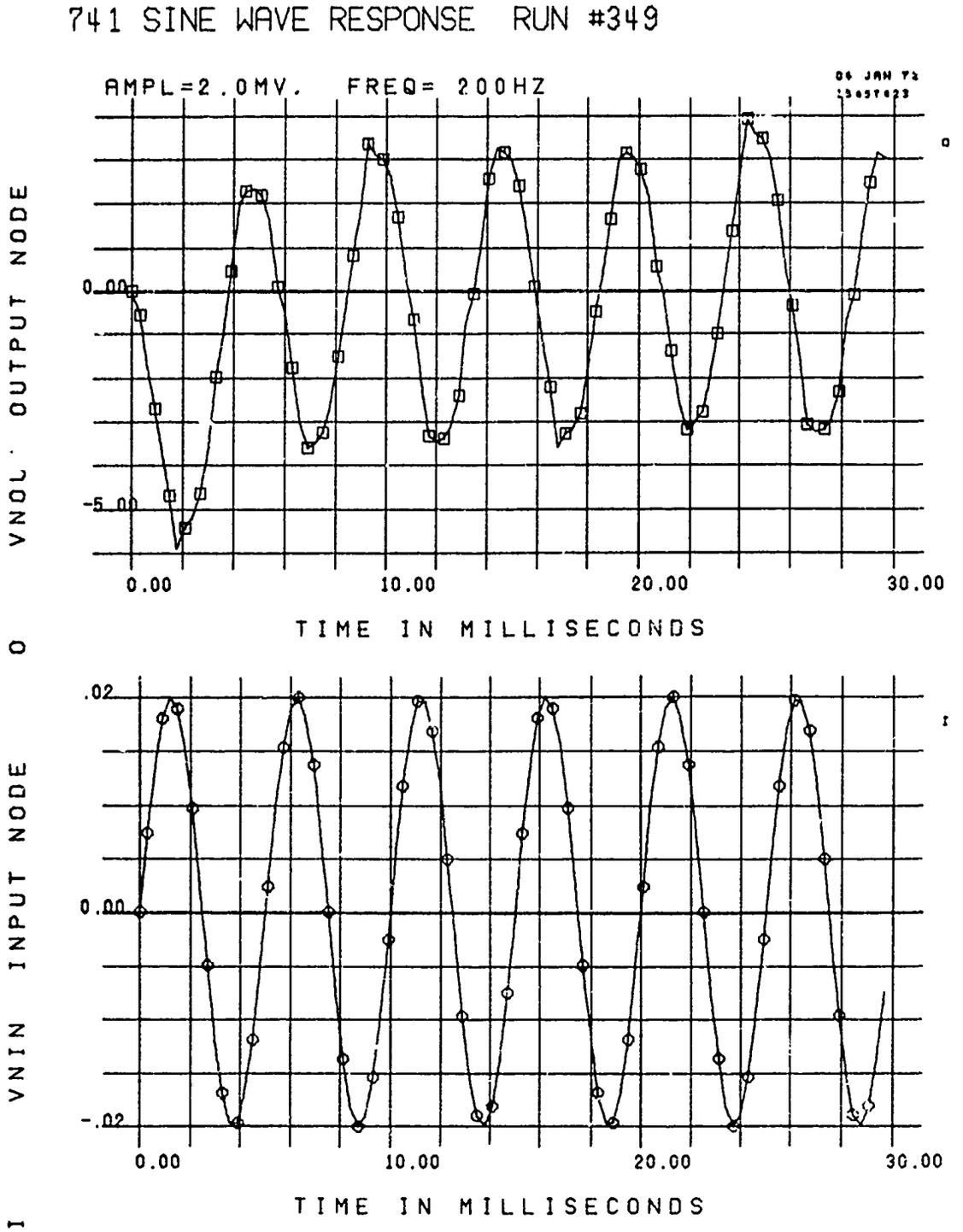


Figure 58g. 741 Response to 200 Hz, 2.0 mv Sine Wave. Rerun of Run 341 with CONVOL Corrected for Multiple Calls by Self-Consistency Loop. Compare with Figure 58f.

a few incorrect terms.

At higher frequencies, above the corner frequency, as evidenced in the results of Figure 58e and f, the initial transient due to turn on of the excitation yields an output response which is distinctly biased in the direction of the initial impulse. This is precisely the result expected by a rigorous theoretical analysis of a linear one pole circuit by Laplace transform techniques. Thus as would be really expected, convolution on the transfer function surface does provide the correct transient solution to the high frequency sine wave stimulus. As time progresses, the response returns to the usual steady state solution with the output swinging equally about the zero voltage axis.

Figure 58g is the rerun of the results presented in Figure 58f in which a bug in CONVOL was corrected that was coming into account when the self-consistency loop in MAIN drove into CONVOL after the first iteration. The interesting aspect to note is that the difference between the two figures is actually very slight, and shows again the stability of a convolutional calculation process against errors in only one term out of a large number. The solution is indeed determined by the entire surface shaping rather than just the instantaneous derivative at the current time step as in the case of a state variable solution.

A comparison of the 741 response to a pulse with and without feedback is contained in Figure 59. The response to the input pulse of Figure 59a, bottom, is shown in Figure 59a, top, and Figure 59b. The voltage at the input node was divided down by a 10k/1k voltage divider to the device input, hence the 741 input level was approximately 1 mv. The output level is seen to be somewhat over 15 volts, yielding a circuit gain of about 15,000. The input pulse rise time was 5 ms, whereas that of the output was 10 ms. This demonstrates again the slowness of the open loop 741.

The time step size used in the calculation for the above case was 5 milliseconds. The fact that a reasonably valid result can be achieved with such a large time constant is interesting of itself.

The pulse response as calculated using the parallel algorithm discussed in Section II for a feedback configuration is given in Figure 59c and d. The feedback resistor was 100K, while the resistance from inverting input to ground was 1K; hence the circuit gain should be 100. The input pulse magnitude was 0.1 at the device. The magnitude of the output is seen in Figure 59c, top, to be 10.0.

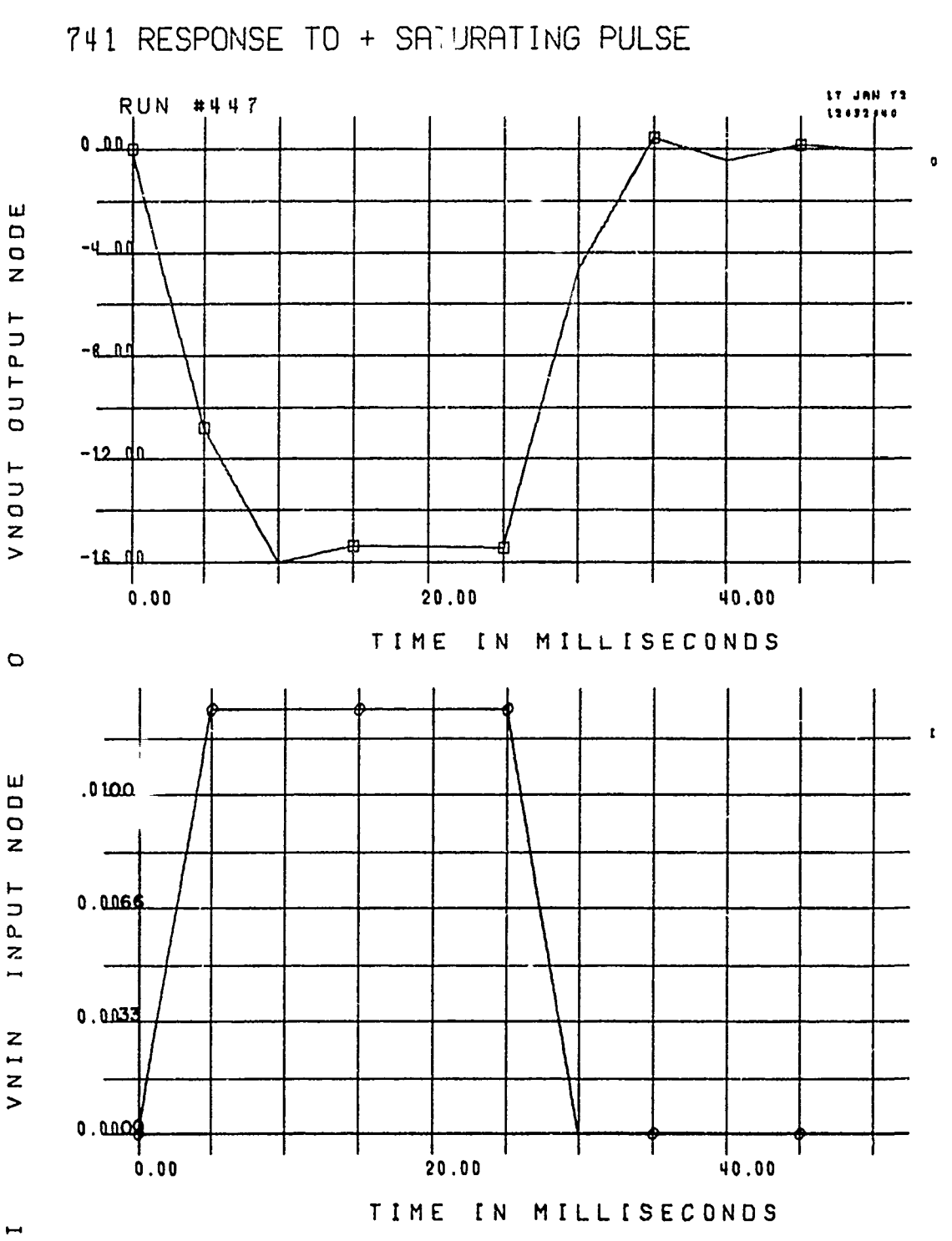


Figure 59a. 741 Response to a Saturating Pulse Without Feedback, Note Output Risetime is 10 ms while Input Risetime is 5 ms.

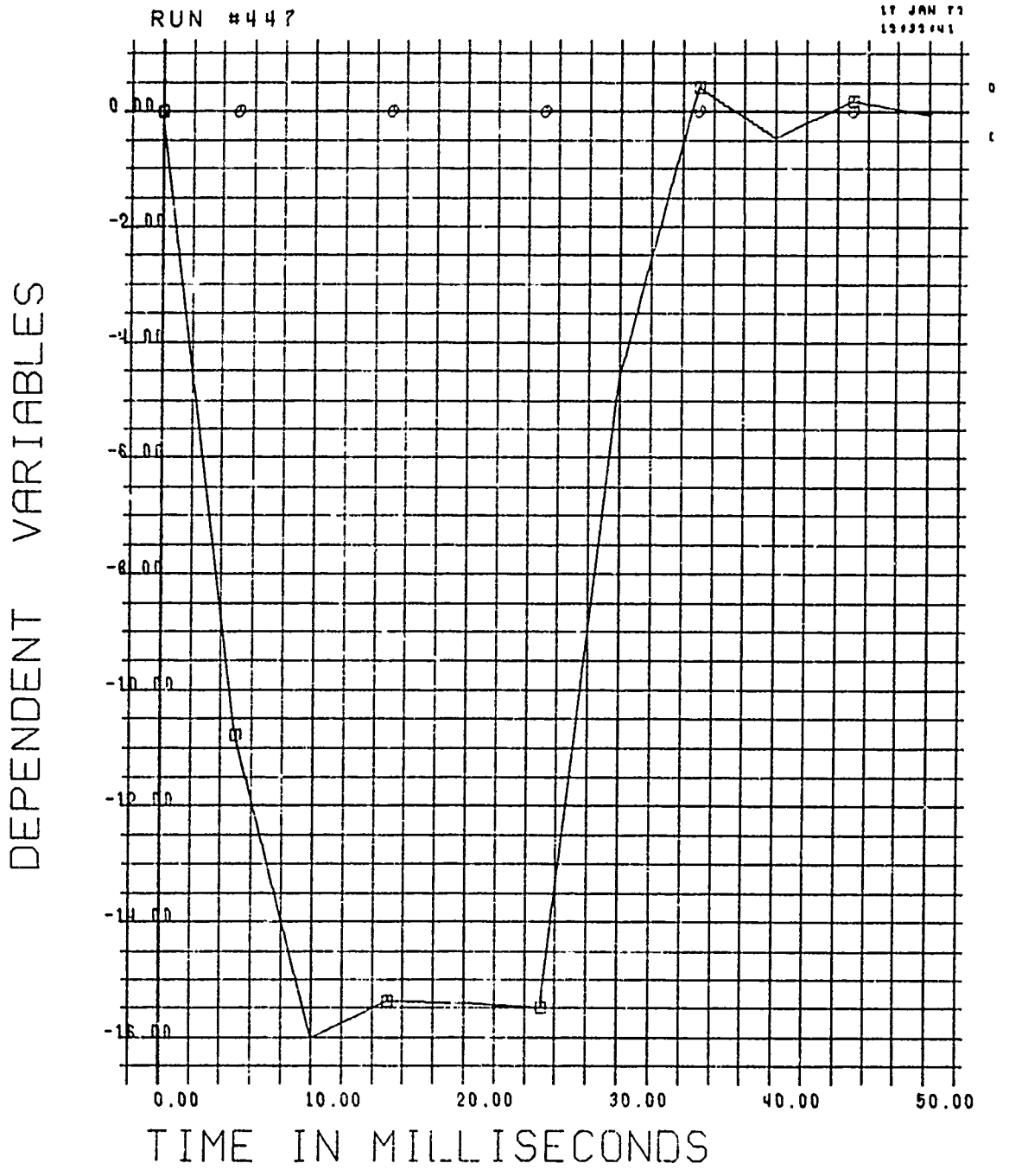


Figure 59b. 741 Response to a Saturating Pulse Without Feedback.

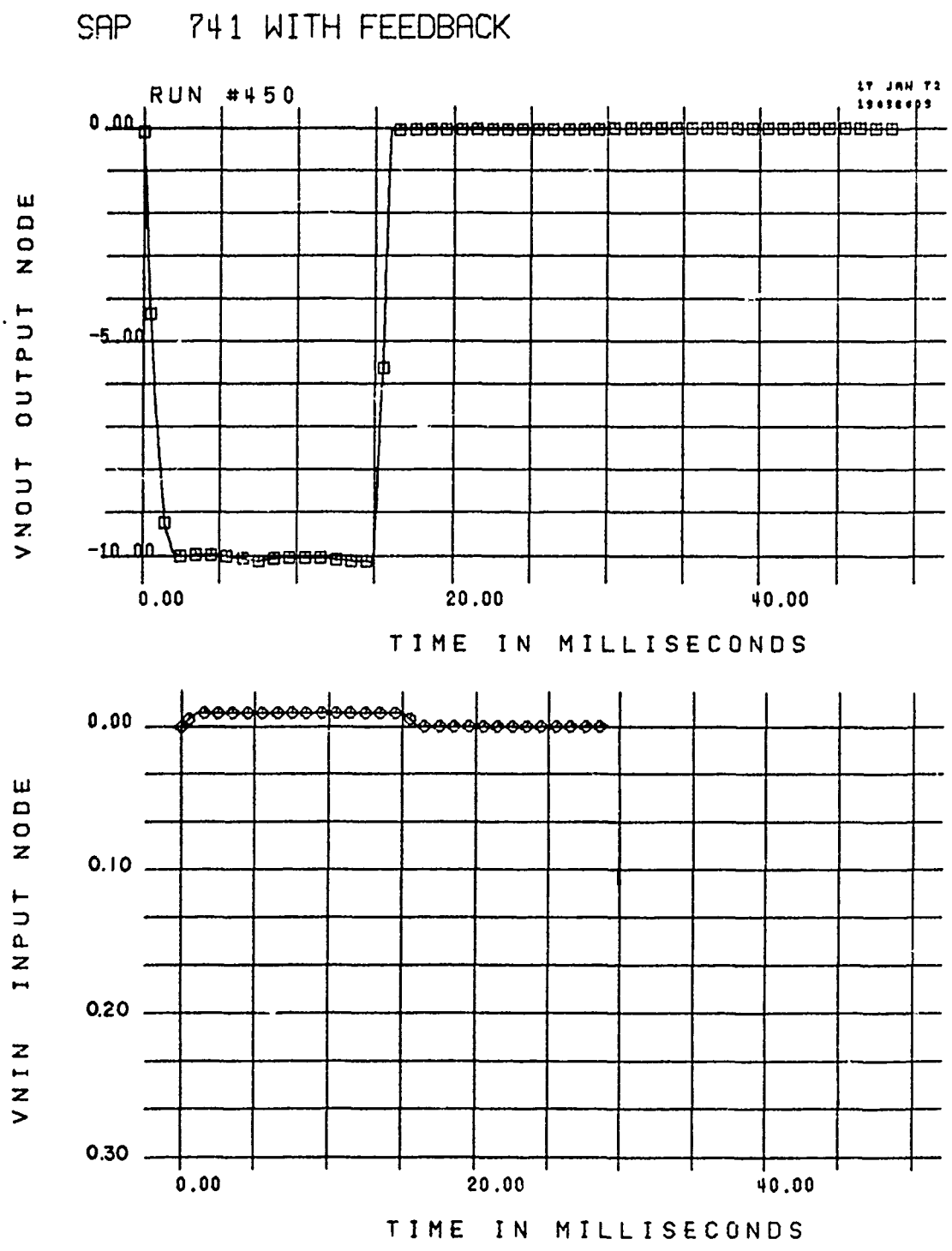


Figure 59c. 741 Response to Same Input Pulse With Feedback, Note Input Risetime is Reduced to 1 ms and the Output Risetime to 2 ms.

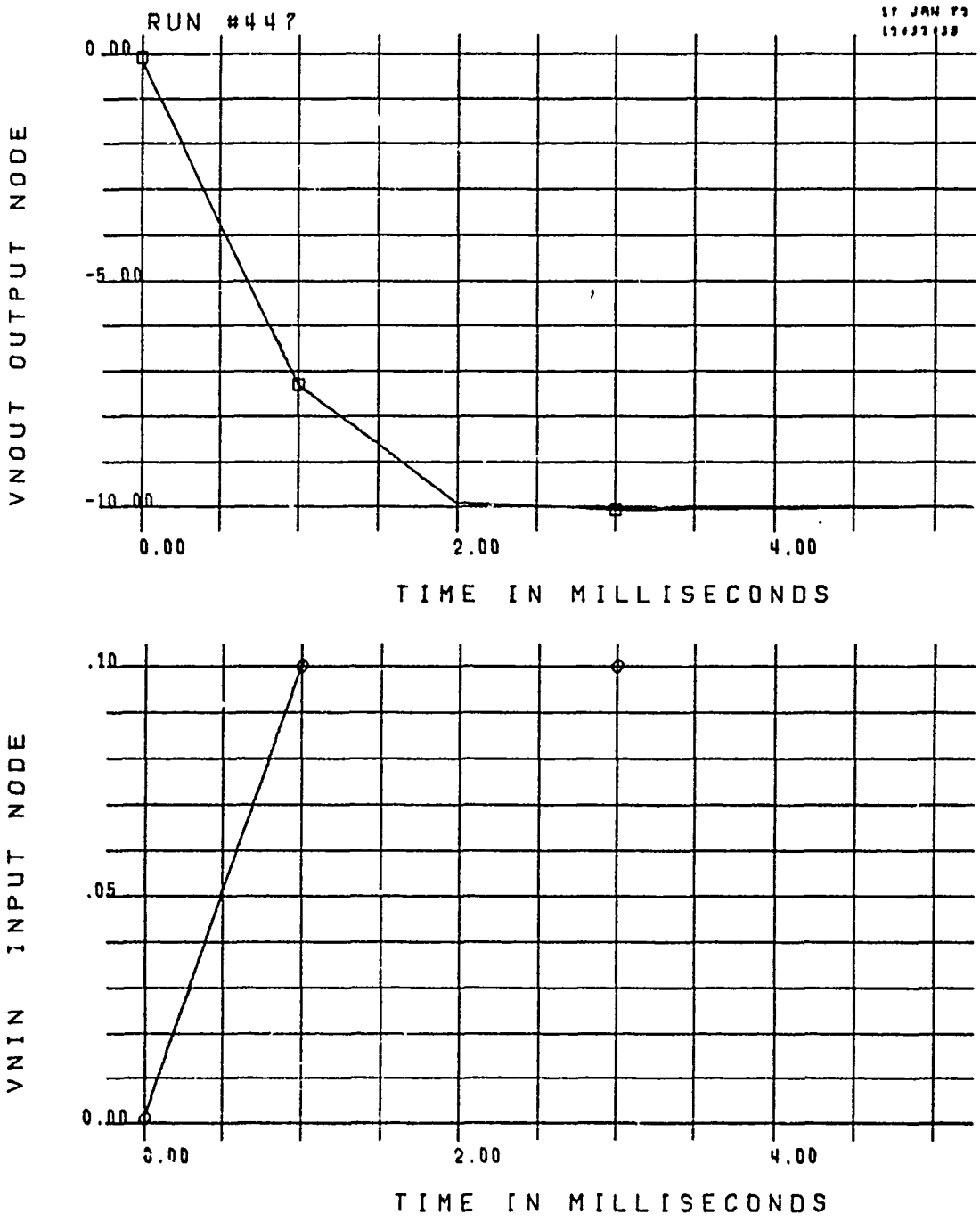


Figure 59d. 741 Response to Pulse With Feedback, Early Time Portion of Waveform.

Hence, the computed circuit gain is in exact agreement with that expected theoretically. This demonstrates that the parallel iteration algorithm does work correctly. The critical aspect of the calculation for this case was the fact that the current splitting between the device input and the feedback resistor differed by a factor of 10^{12}. The use of double precision arithmetic would seem advisable in such cases. Nevertheless, the results of the single precision calculation by PARLEL do seem satisfactory here.

Note also the higher response speed of the 741 in the feedback configuration as compared with **open**loop case. The output pulse rise time seen in Figure 59c, top, is 2 ms; which is five times faster than that obtained in Figure 59a, top, for the open loop case.

An important point is correctly selecting the EPSLON convergence criteria which the iteration loop in MAIN and the current splitting loop in PARLEL are driving towards. A relatively loose criteria is needed in the parallel iteration loop; in the case above 0.1. This seems rather large when compared with the parts per million convergence routinely achieved on the fixed output variable. On the other hand, a computational validity of 0.1 v out of 10.0 v is a relative precision of 1 percent. In experimental electrical engineering activities that degree of precision is regarded as acceptable.

The essential point deduced by detailed analysis of the printed listings of the parallel iterations runs was the inner parallel iteration loop should have a loose convergence criteria particularly at the beginning of the outer iteration, and then can be tightened up as the outer iterate is improved.

In a test run using linear resistors connected in parallel, the inner loop converged exactly on the second iterate. With a smaller spread of current splitting factors, the single precision computation is less a problem. However, the convergence criteria of the inner loop had to be about two orders of magnitude tighter in this case, or approximately the same as that of the outer loop as controlled by DRIVER.

2. 741 OP AMP - RADIATION RESULTS

In the foregoing, only two stimulus functions, the voltage and current driving into a block were taken into account by SAP. These were then propagated through

the system blocks by the successive block transfer functions. With radiation applied, one or perhaps two additional forcing functions are driving the system response, namely φ_X and φ_N, representing the X-ray and neutron dosage functions. The manner in which these forcing functions act on the system is different from the electrical stimuli in that they act simultaneously on all blocks. This difference is shown schematically in the block computational diagram as shown in Figure 60. The electrical response of the block to the radiation stimulus still propagates in the normal sense however.

The radiation voltage and current transfer functions are shown tied onto the radiation stimulus lines essentially in parallel, with the outputs summing into the block output terminals.

A basically interesting point now arises in relation to the fundamental iteration procedure that SAP uses to solve the system problem. Before with just electrical stimulus, one input variable was fixed and a modified Newton's method iteration algorithm applied to the adjusted input variable to meet the prescribed output constraint condition on the fixed output variable. Now with a radiation stimulus also acting, additional phenomena are occurring which are outside of the normal iteration loop. This is tantamount to the realization that the driving function is an independent variable for the case of radiation, but which is not true for the adjusted input variable. On this basis, the radiation terms were excluded from the iteration process taking place on the adjusted input variable.

The block input and output impedances are represented in Figure 60 as Z_{in} and Z_{out}. For a linear element, these would be very simple and perhaps best represented by an appropriate equation for the particular circuit element. For digital circuits, a machine fit to the experimental characteristics may be best. Such characteristics were taken at the SPR for the gates, and showed relatively small change with successive exposures.

Voltage and current radiation transfer functions are shown in Figure 60 for each block element. In our measurements at the Kirtland FXR or the Sandia Pulse Reactor (SPR), it seemed that one or the other are primarily important. The other may be small, or perhaps linearly related. Hence it does not seem always necessary to resort to a surface representation for both independently.

The radiation forcing functions programmed into RADGEN are piecewise linear, Gaussian, and Weibull distributions. The SPR radiation waveshape in time is

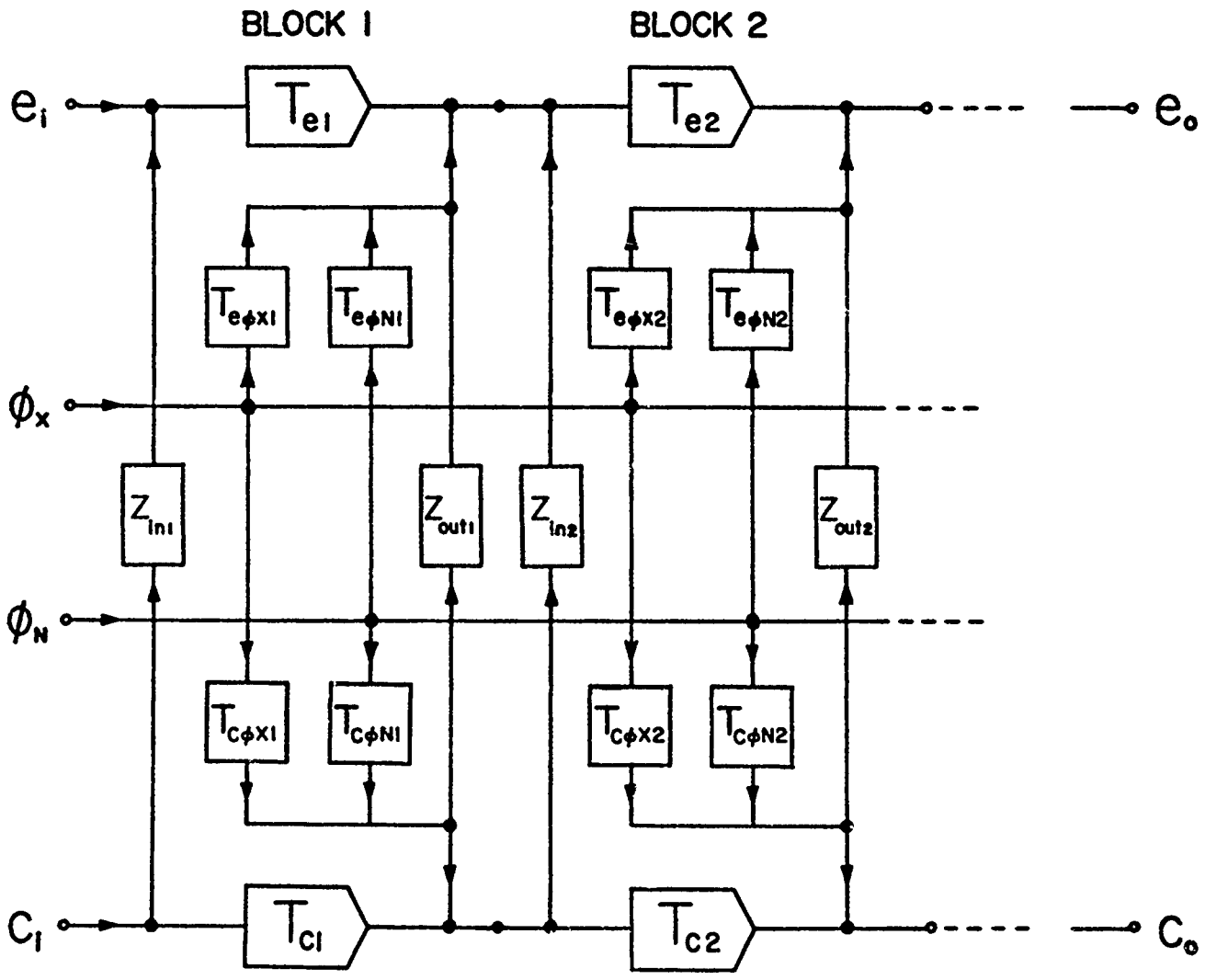


Figure 60. Schematic Computational Block Diagram Indicating How Radiation Drives Simultaneously into all Blocks.

approximately Gaussian; however, some assymetry is evident in the shape relative to the peak. This type of asymmetry can not be achieved by a Gaussian distribution. The Weibull distribution is more flexible in that vastly different shapes can be generated by adjustment of the shape parameter. The equations for these two distributions are :

Gaussian

$$p(t) = \frac{A}{\sigma\sqrt{2\pi}} \exp - \frac{(t-\tau)^2}{2\sigma^2}$$

wherein A = amplitude, σ = width parameter, and τ = time of peak;

Weibull

$$p(t) = \beta\, \alpha^{-\beta}\, (t-\gamma)^{\beta-1} \exp - \left\{ \frac{t-\gamma}{\alpha} \right\}^{\beta}$$

in which α = time scaling factor, β = shape determining factor, and γ = time location parameter. The value of γ is usually zero. For the shape parameter β equal to a large positive number, say about ten, the Weibull distribution is a narrow peaked distribution like a Dirac delta function and α is the time at which the peak occurs. For $\beta = 1$, the Weibull distribution becomes an exponential. We judge that a value of β about 3 approximates the SPR radiation waveshape.

By inspecting the mode of calculation given in Figure 60, and neglecting for simplicity the input-output impedance terms, it is possible to write a closed form expression for the system output voltage and current in terms of the transfer functions and the input stimuli. Suppose for example, that we had three blocks and looked at the voltage calculation, the terms that enter into the machine computation are:

$$e_{o3} = T_{e3}\left(T_{e2}T_{e1}e_1 + \left[T_{e2}T_{e\varphi 1} + T_{e\varphi 2} \right]\varphi \right) + T_{e\varphi 3}\,\varphi$$

Or, in the general case

$$e_o = \left\{ \prod_{j=1}^{JMAX} T_{ej} \right\} e_i + \left\{ \left[\sum_{j=1}^{JMAX-1} T_{e\varphi j} \prod_{k=j+1}^{JMAX} T_{ek} \right] + T_{e\varphi JMAX} \right\} \varphi$$

with a similar expression for the current. While the above expression is nice in terms of being able to reduce the operations into a form of transformations acting on the stimulus functions, the machine calculations more closely follow

the computational strategy contained in the block diagram format of Figure 60.

An interesting phenomena came to light in the machine computations, namely with small but non-zero values of the voltage stimulus variable on the input, the iteration procedure does not have sufficient signal upon which it can operate so that it can significantly effect the output. Hence if factors such as digital noise, or carryover from the radiation terms upset the output result, the iterate is too small to overcome and null them. This meant that those runs which had a simultaneous electrical signal applied during the radiation pulse yielded a more stable iteration pattern than runs where the electrical stimulus was small or non-existent. The solution to this problem consisted of isolating the radiation terms from the iteration process, and eliminating carry-over of prior computation elements by the self-consistency loop.

The very first runs that attempted to calculate the radiation response did have a concurrent electrical signal; consequently the iteration was very stable as the curves of Figure 61 and Figure 62 nicely show. Figure 61a (bottom) is the response to a FXR pulse of dose $\dot{\gamma} = 10^{10}$ and an electrical pulse of 1 mv, as shown in Figure 61a, (top). Figure 61b is the combined plot. A logarithmic time base was used in this calculation, covering seven orders of magnitude in time in 100 equi-interval log (time) steps.

The radiation first drives the output negative, and then up into positive saturation until a time of about 5 ms. The electrical input then becomes effective and drives the output down and dies away. Since the radiation simulation is that of an FXR burst, convolution of the radiation surface was not necessary; rather just one partition was driven back along an isodosal. The electrical response represents the result of convolution of many partitions along the T_e surface. Three surfaces were resident in core for the run -- TE741, TRX741, and TRN741.

The result of superimposing a SPR neutron burst with the same electrical pulse is shown in Figure 62. The initial positive and then negative voltage swing results from the valley present in the 741 SPR surface, Figure 23, at high dose. Note how the electrical term is more significant here than in the case of an FXR burst since the SPR burst is relatively slower in time by about three orders of magnitude, and at the high dose end of the SPR surface, degradation has reduced the long time radiation response. This run was executed prior to the incorporation of the routine DAMAGE into the computation.

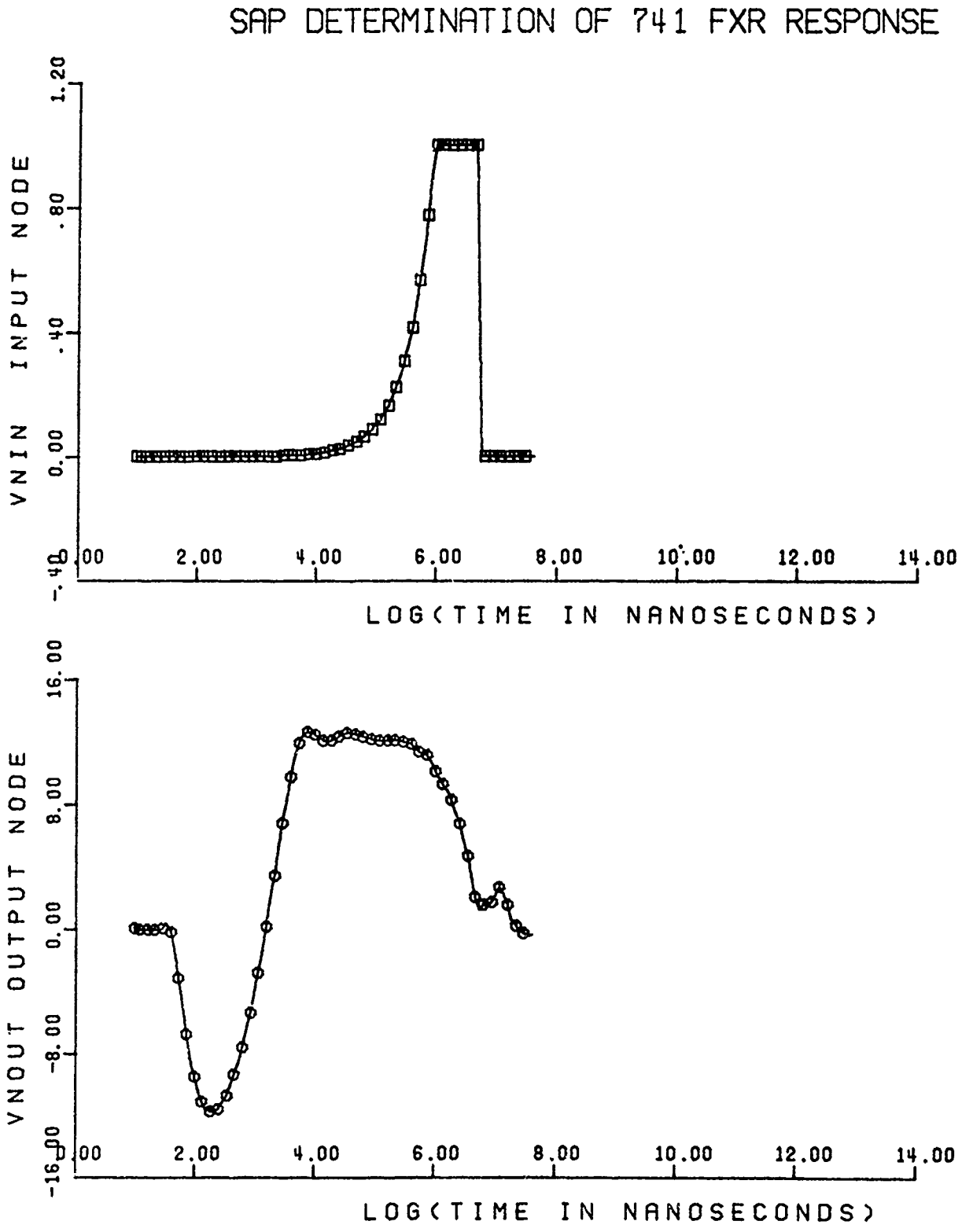


Figure 61a. 741 Response as Calculated by SAP to both Electrical and Radiation Stimulus, FXR Dose is $\dot{\gamma} = 1.0 \times 10^{10}$.

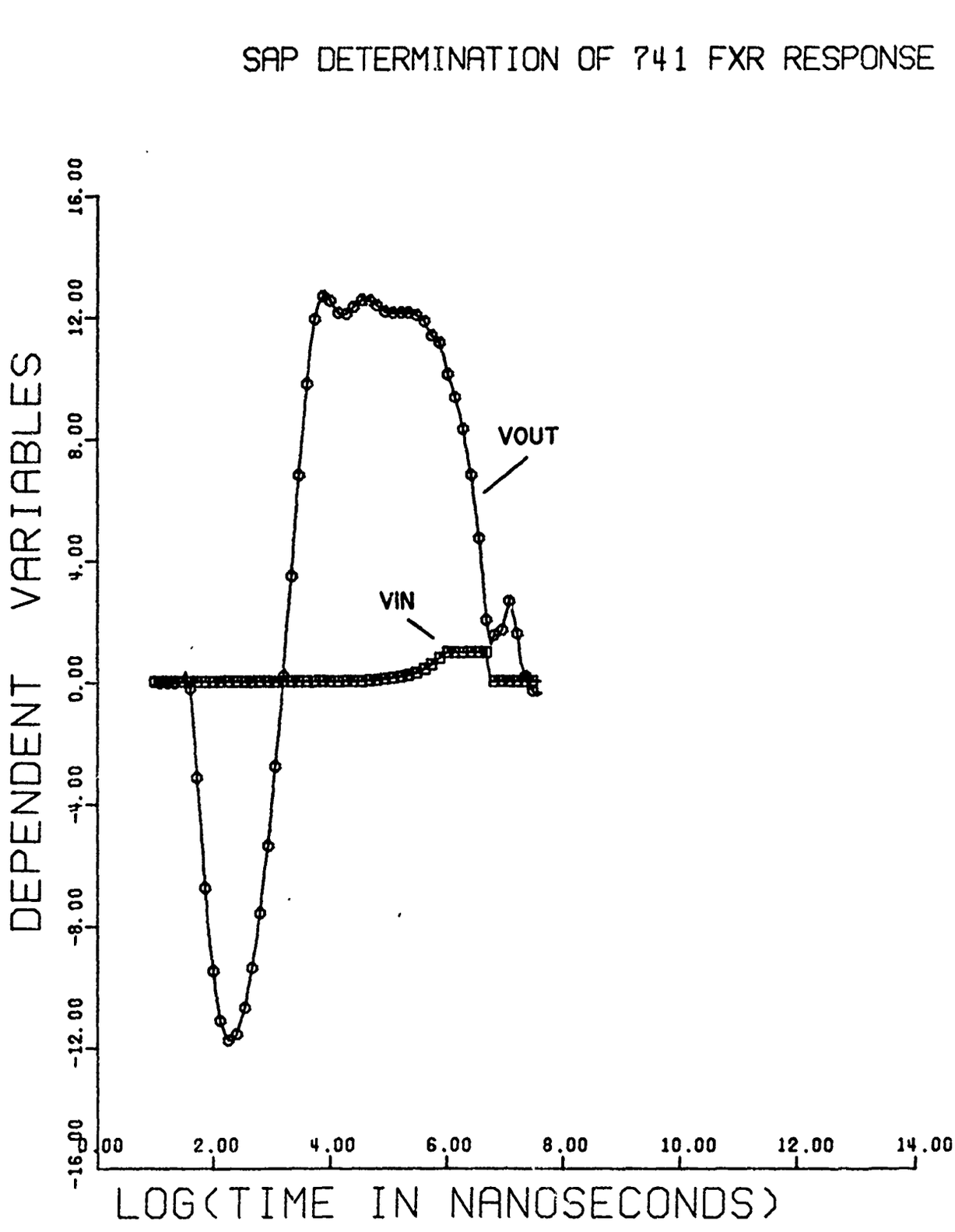


Figure 61b. 741 Response to Both Electrical and Radiation Stimulus. Note Log(Time) Base Covers Seven Orders of Magnitude in 100 Steps.

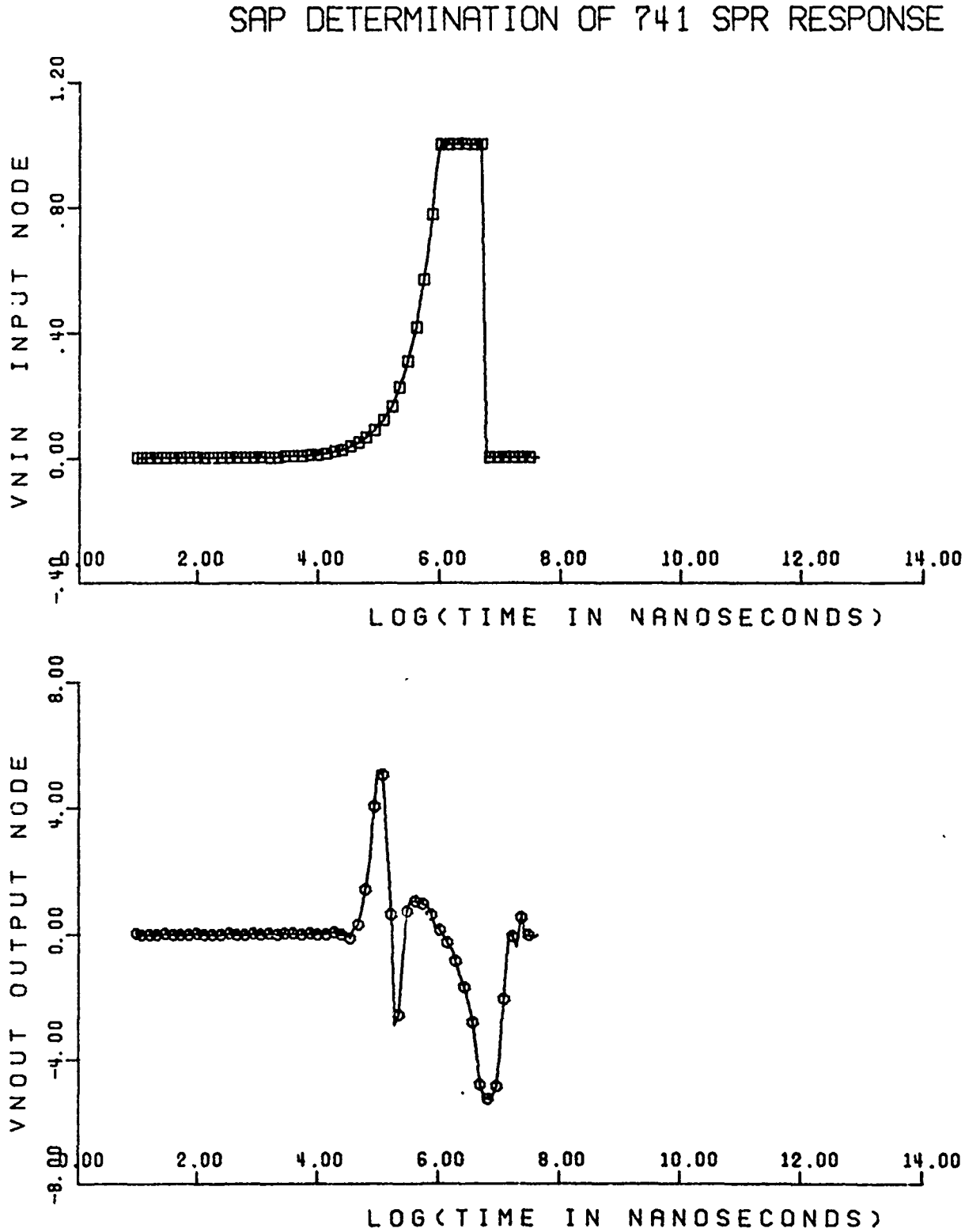


Figure 62a. 741 Response Calculated by SAP to both Electrical and SPR Radiation Stimulus, Neutron Dose is 7×10^{13} nvt/cm^2.

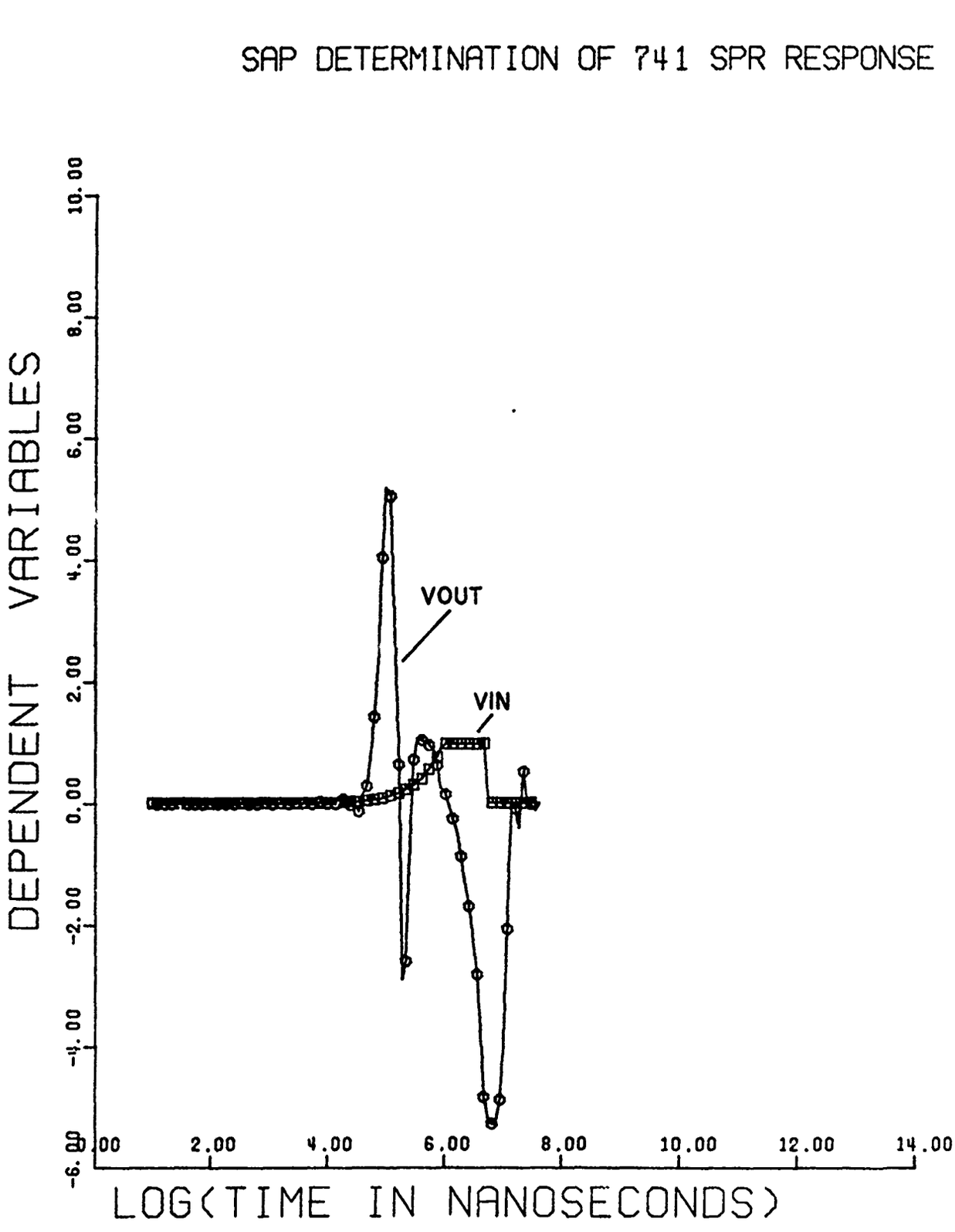


Figure 62b. 741 Response Calculated by SAP to both Electrical and Radiation Stimulus.

The results presented in Figure 61 and Figure 62 were obtained on the same job submission in about one minute execution time on the Univac 1108. File manipulation, and compilations if any, typically extend the execution time another 30-40 seconds. The computations are extending over seven to eight orders of magnitude in simulation time. The calculational time base and the plot time base were both logarithmic. If a linear plot scale is used, the fast early phenomena are invisible.

The FXR simulation of Figure 63 is for a somewhat lower dose level of $\dot{\gamma} = 6.8 \times 10^7$ and no electrical stimulus. There are actually four curves of significance on the figure, rather than the evident three. The top curve is the output current in milliamperes. The center curve is actually two curves lying on top of each other. The plus symbols denote the radiation response alone; the squares denote the superposition of that with the electrical output. Since the input, as given by the curve on the zero voltage line by diamonds, is zero, the degree of success of the iteration process in MAIN is indicated by the difference between the two center curves. A small difference means the process is working well, a large difference contrariwise. Figure 64 is a SPR simulation for a dose of 10^{13}.

3. 9704 NAND GATE ELECTRICAL RESPONSE

The electrical response of the 9704 gate is calculated using the surface depicted in Figure 26. Since the z coordinate of the surface directly returns the output magnitude, rather than a transfer function, the multiplier UMULT on the convolution terms in CONVOL is set to the value one rather than the stimulus variable UIN, as can be seen in the listing of Figure 52c. Also since the surface represents the results of first turning on, and then turning off the pulse, if a partition continuously moves back along the surface two output pulses are generated, one at the turn on transition, and one at the turn off transition. This yields a double pulse of opposite polarities, as is shown in Figure 65 (top). The input pulse that generated it is shown in Figure 65 (bottom). It is seen that the first pulse is a reasonably good approximation to the real device response as shown in the x-y recorder tracing of a sampling oscilloscope output given in Figure 66.

By simply setting the value of XHIGH for the surface of Figure 26 to a value of about 200 ms, TSURF returns the surface z value at XHIGH when the call from

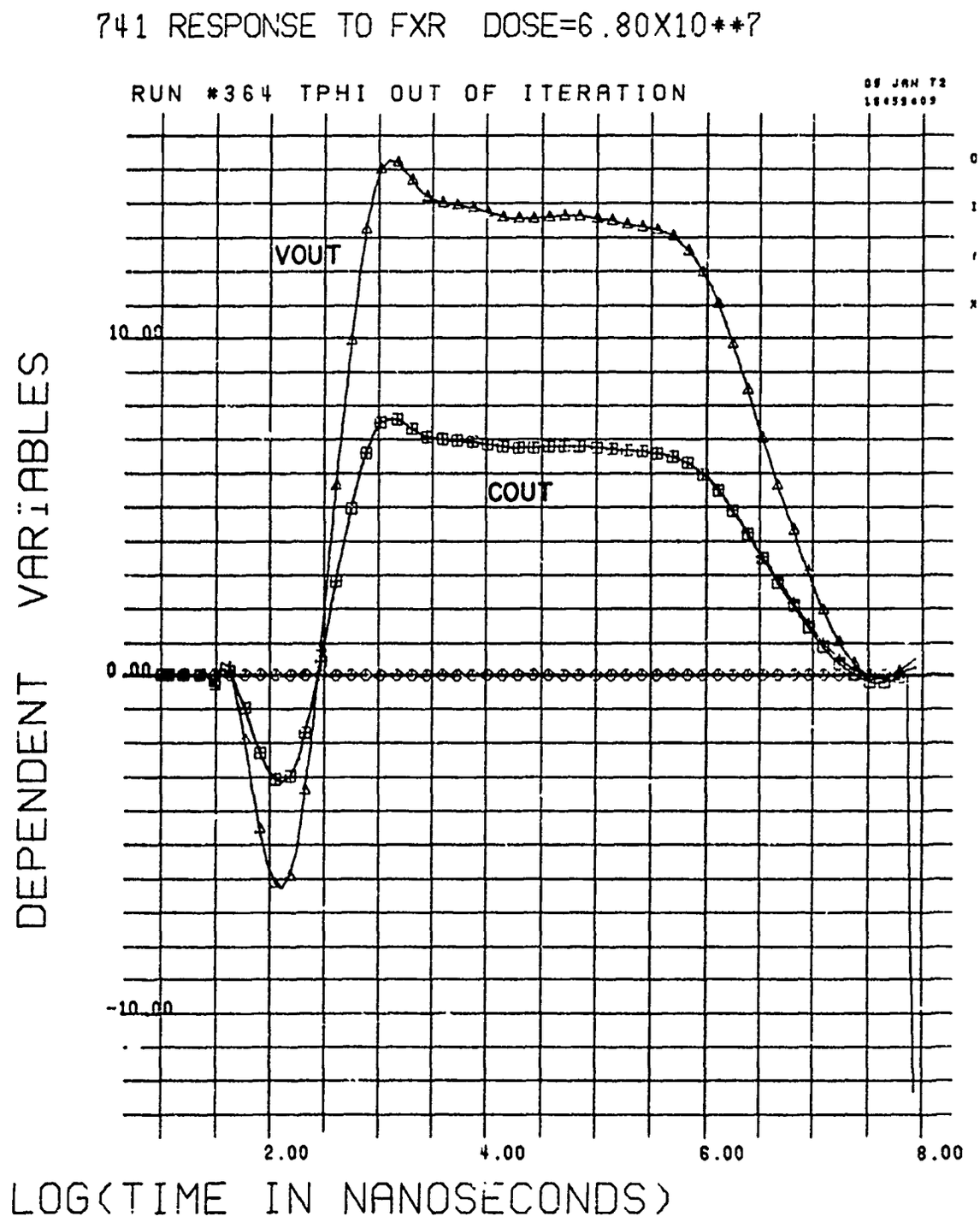


Figure 63. SAP Simulation of 741 Response to FXR Pulse.

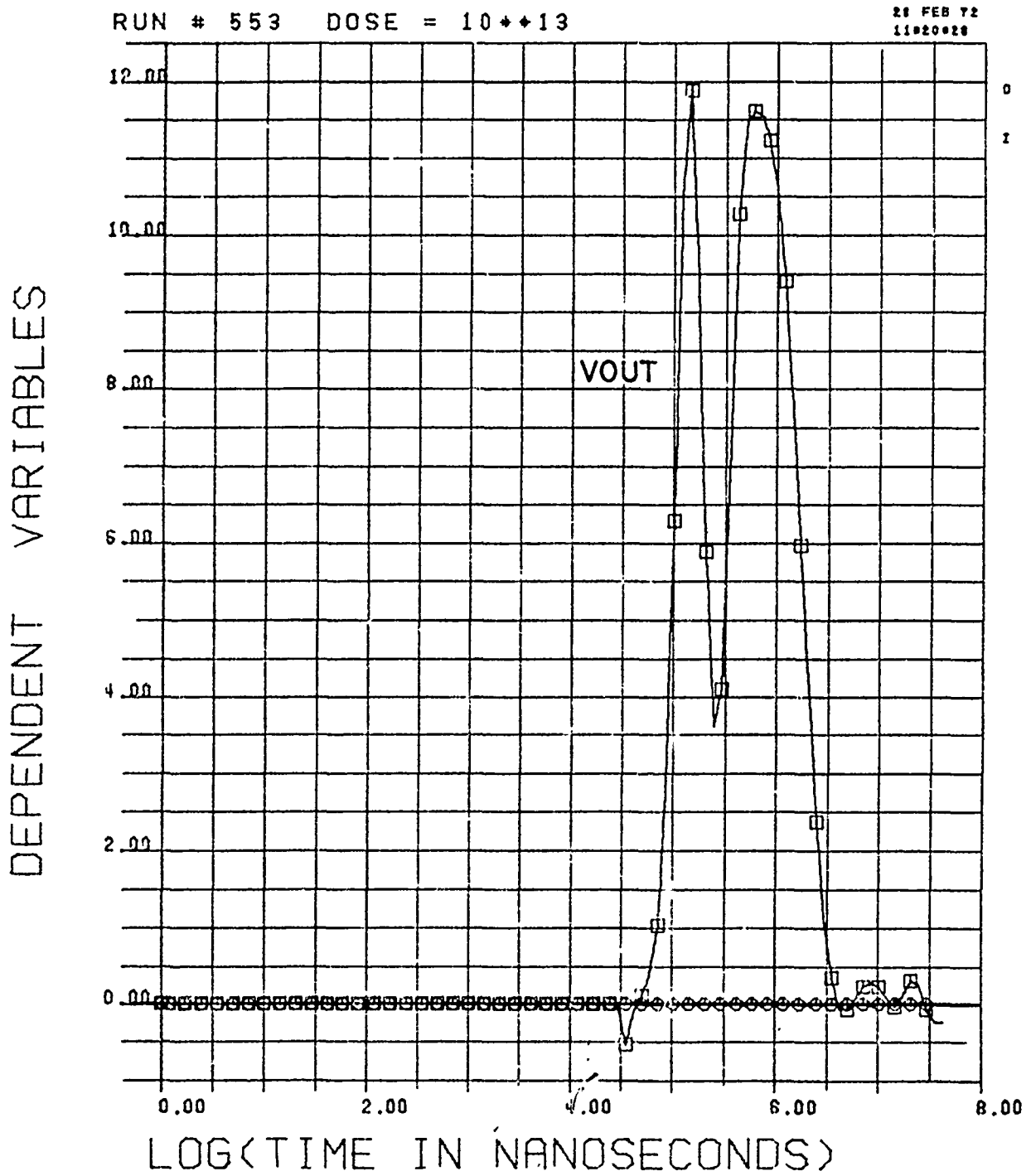


Figure 64. SAP Simulation of 741 Response to SPR Burst.

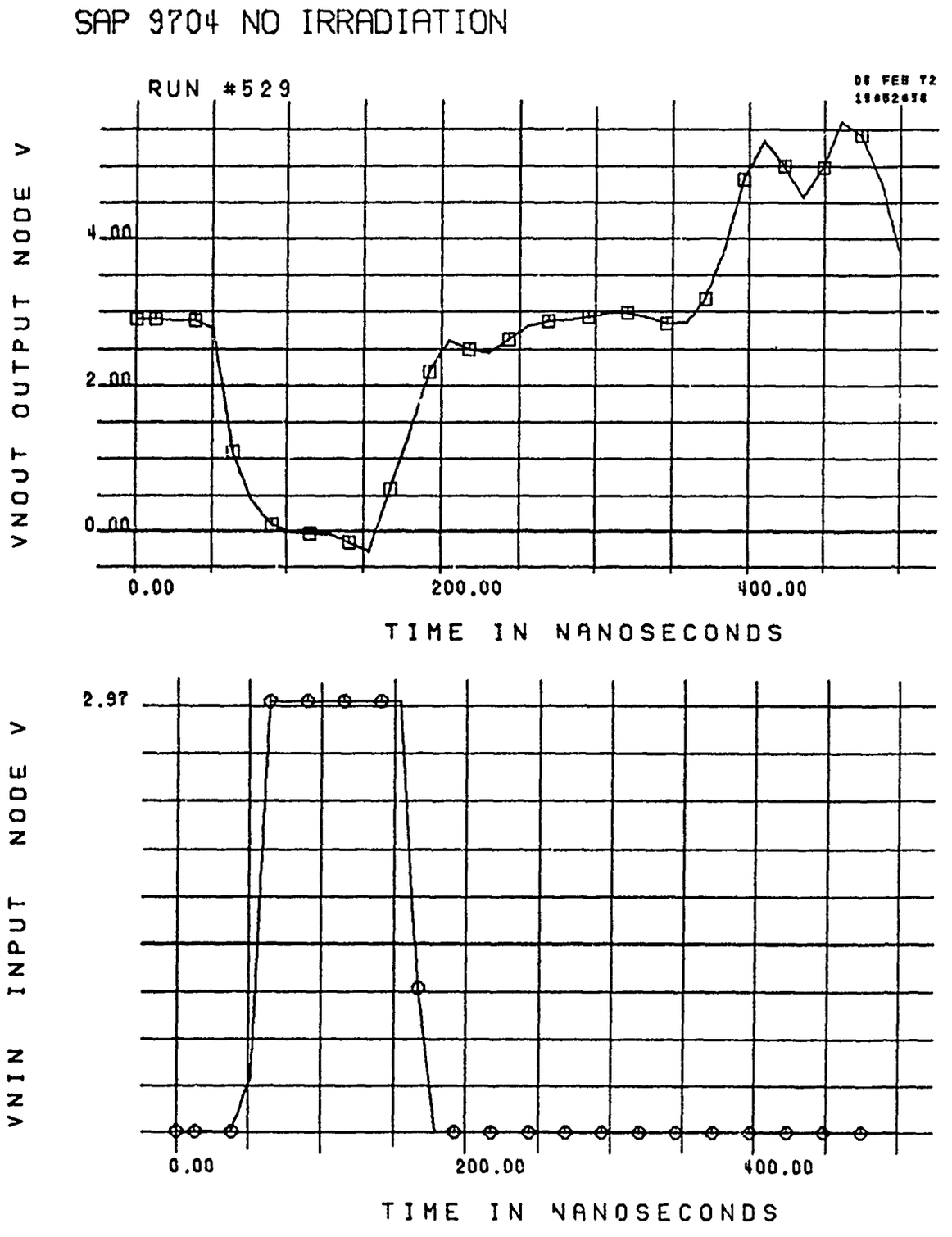


Figure 65. SAP Calculation of 9704 NAND Gate Response to Electrical Pulse.

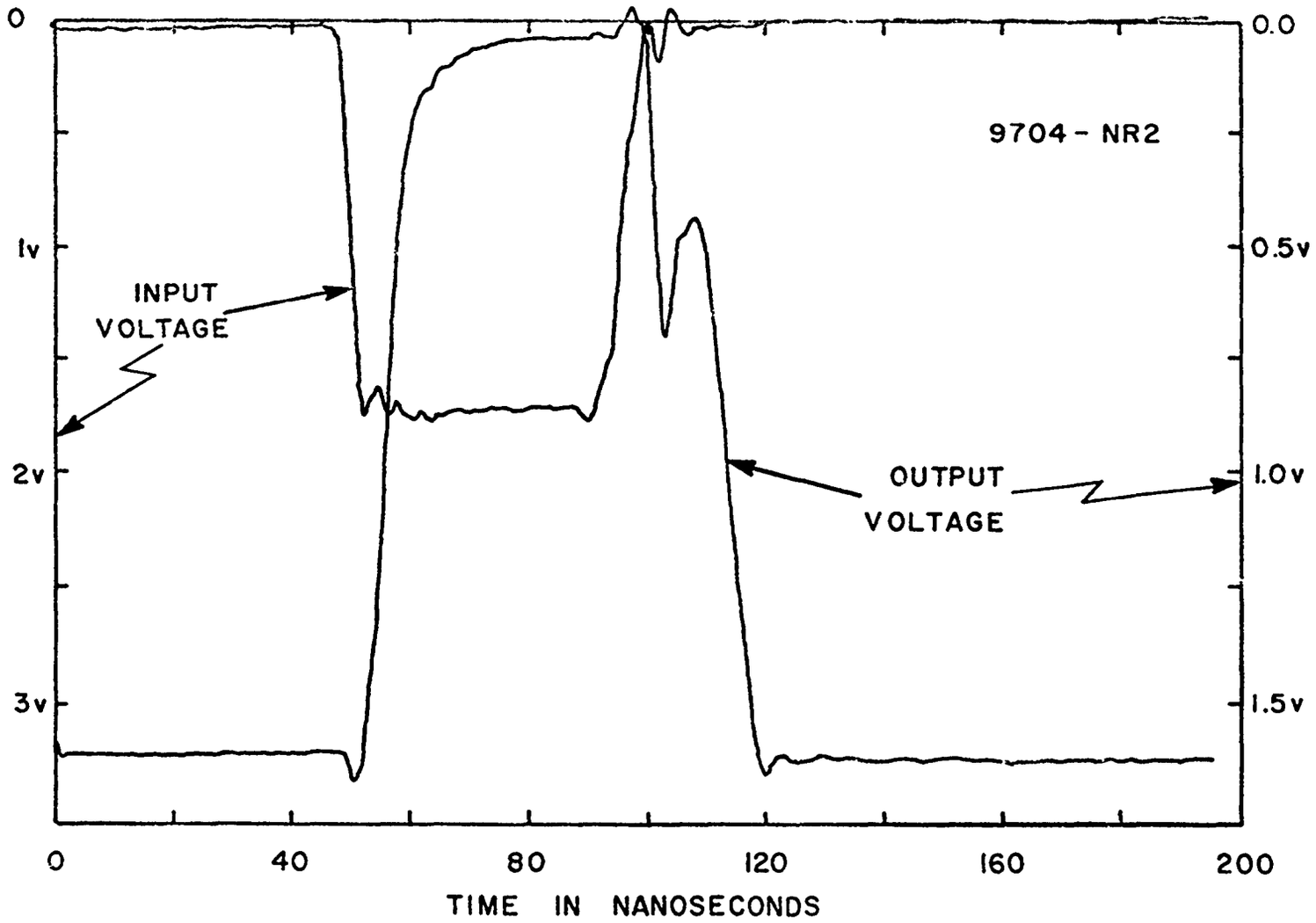


Figure 66. X-Y Recorder Tracing Made with a Sampling Oscilloscope of 9704 NAND Gate Response to a Pulse Input Waveform.

CONVOL has a time coordinate exceeding XHIGH. The result is to delete the second pulse as is shown in Figure 67. The rise after the pulse is resumably due to the surface structure just ahead of the new XHIGH value. Further computer experiments would consist of further reduction of XHIGH or smoothing of the surface in the low state. There is however a fairly good simulation of the rise and fall times of the real device. Thus even with the relatively preliminary nature of the results presented here, it appears that convolution on experimentally obtained input-output surfaces can yield dynamical representations of device performance which are fairly good.

One aspect of work on which effort was not expended because of the limited time span available was the modeling of multiple inputs to the gate. There are at least two ways of doing this. One is to use logical AND statements on the individual input signals to ascertain the logic state, and to obtain the dynamics then by taking the equivalent composite pulse and running it back along an isovoltage loci on the surface. Thus, convolution would <u>not</u> be required. This essentially is equivalent to presuming that the input pulse rise times are all very short, rather than like a slow ramp. The alternative procedure is to convolve each individual pulse along the surface and sum the outputs moduloed down by the number of inputs N. Thus, the switching threshold would be N times the individual input threshold. If the sum is more than the N threshold, then the logic device switches.

The actual device has multiple emitters on one transistor. That transistor essentially forms a composite input waveform to the emitter-base junction. The junction really does not see separate waveforms coming in. The input transistor operates in grounded base configuration, and is fast since the alpha rather than the beta cut-off frequency is applicable. The slowness of the entire circuit is due to the fact that the following transistors operate grounded emitter. The logic function arises at the input since if any one emitter is down, it hogs all the base current and keeps the input transistor on. Only when all the emitters are high does the input transistor turn off, and so turn on the following stage. After the first input transistor, the circuit is the same as a single input device. The logic thus occurs right at the input as in other T^2L devices.

Thus, since the input device is fast, and the logic occurs immediately, it would appear reasonable to use a logical IF statement to perform the logic function, and the surface to generate the total dynamics from the composite waveform thus created.

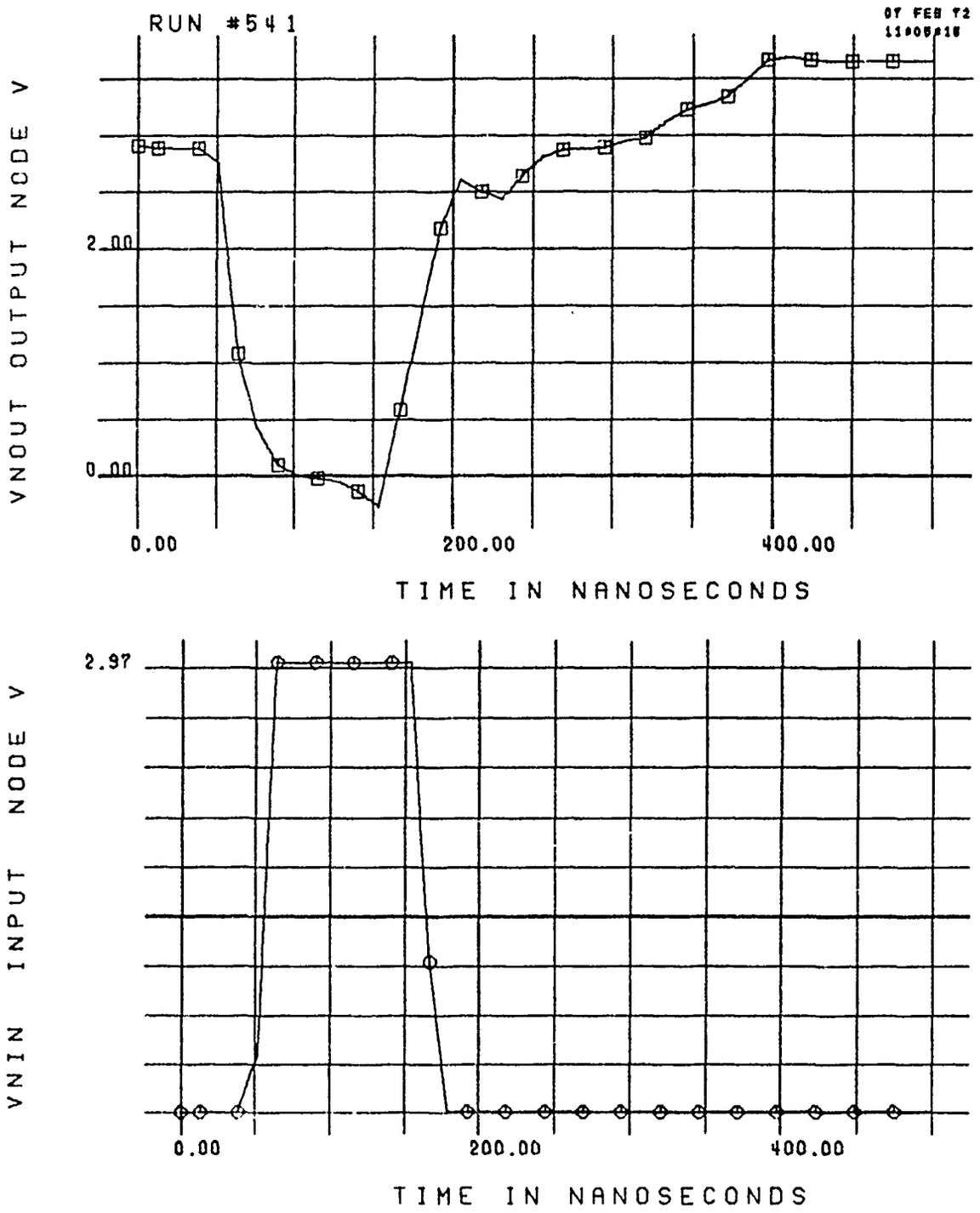


Figure 67. SAP Calculation of 9704 Response to an Electrical Pulse After XHIGH was Lowered.

The convolutional approach on the individual input waveforms would appear better in cases which are more apt to have input stimuli which are slow or have uncertain voltage levels, perhaps lying in the transitional range. Then the motion of the partitions on the surface would sample the slow, long-time constant, transitional region of the response surface.

The merit of these two methods should be ascertained in any future work with the general ideas discussed in this report.

4. 9704 NAND GATE RADIATION RESPONSE SIMULATION

The combination response to an FXR pulse and the voltage waveform shown in Figure 68 (bottom) is presented in Figure 68 (top). This represents the output as calculated using the voltage response surface (Figure 26); the radiation voltage response surface (Figure 39); and the radiation current response surface (Figure 40). The device was loaded with a 500-ohm resistor rather than another gate. The computed waveform seems to be primarily determined by the basic electrical response alone because the dosage $\dot{\gamma} = 1 \times 10^{10}$ is below the level at which a significant excursion occurs on $T_{\varphi V9704}$ as in Figure 39. The magnitude of the radiation terms in Figure 68 (top) are only about 0.1v in magnitude and so do not dominate the electrical term.

The first attempt at the neutron simulation is shown in Figure 69. The plotted output became very large and negative near the end of the calculation. This was seen, by looking at the listings of the convolution sums, to be due to the continuing contribution of partitions on the T_e surface which had reached the end of the surface and were continuing to contribute ever larger and larger values to the sum by virtue of the logarithmic increase of the time step multiplier coming into play as time went on. Since the surface terminates at 450 ns, a partition whose time step multiplier is in the millisecond range makes a very large contribution in the calculation even though its dynamic effects are long past.

The cure to this problem turned out to be relatively simple as shown in the TSURF listing of Figure 53, when the time entry look-up variable exceeds 10 times the XHIGH value for the surface, simply return the value zero to CONVOL. The resulting change in the calculated result is shown in Figure 70. For this particular run, four surfaces were resident in core and were being used simultaneously during the calculation. These surfaces are:

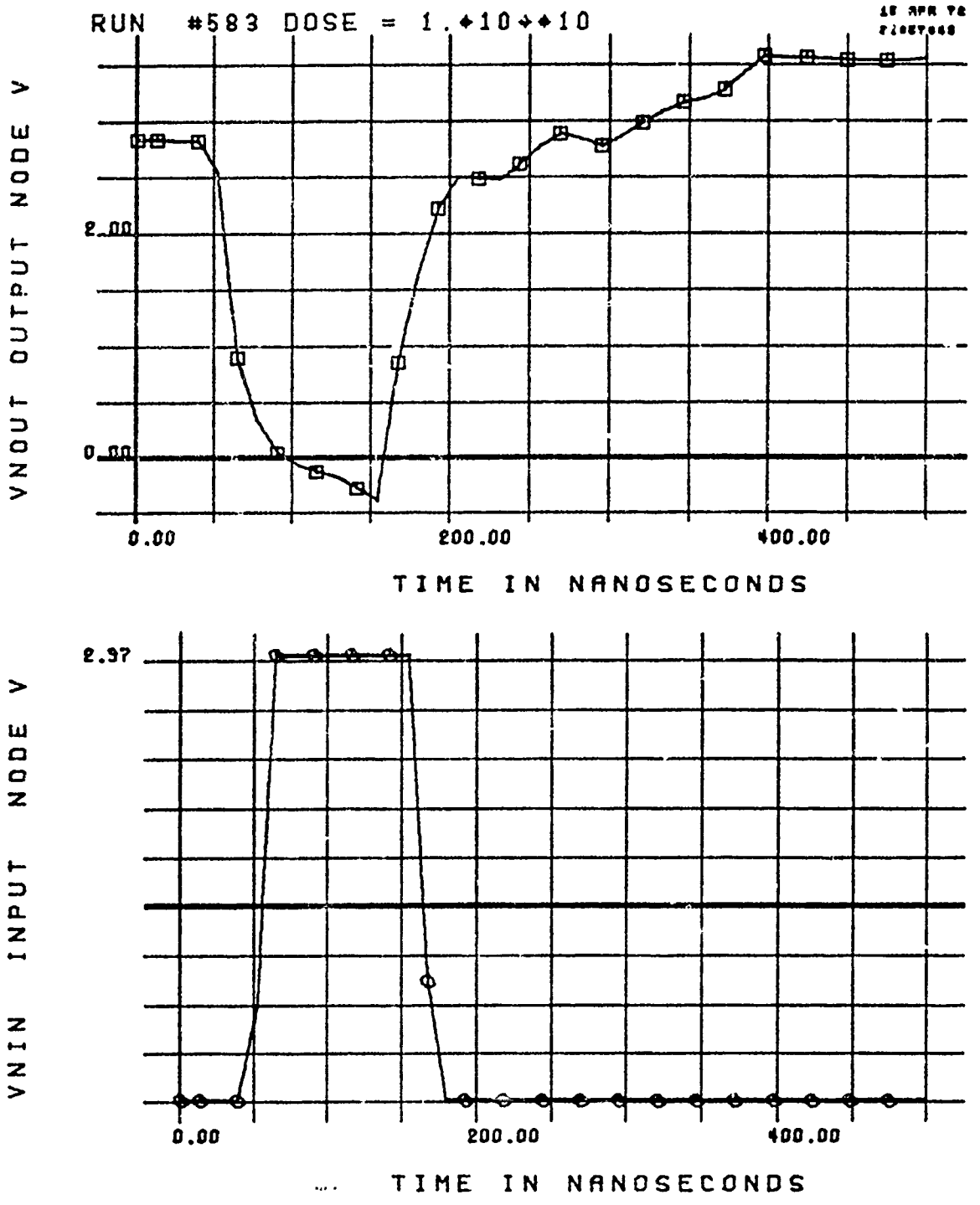


Figure 68. SAP Simulation of 9704 with Electrical Pulse and FXR Radiation Dose = 1.0×10^{10}

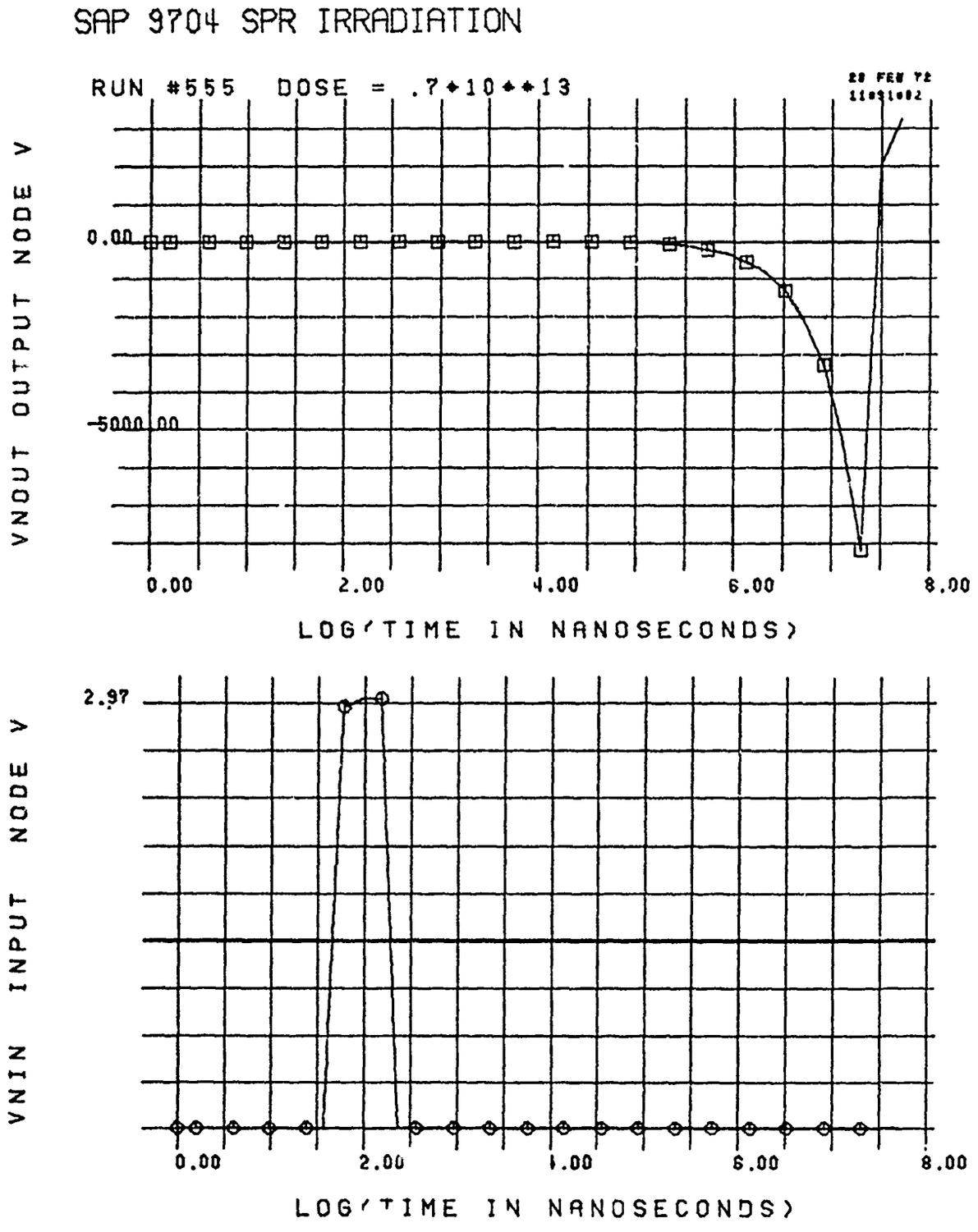


Figure 69. First SAP Simulation of 9704 Neutron Response with Electrical Pulse. Log(time) Base and Large XHIGH Caused Divergence.

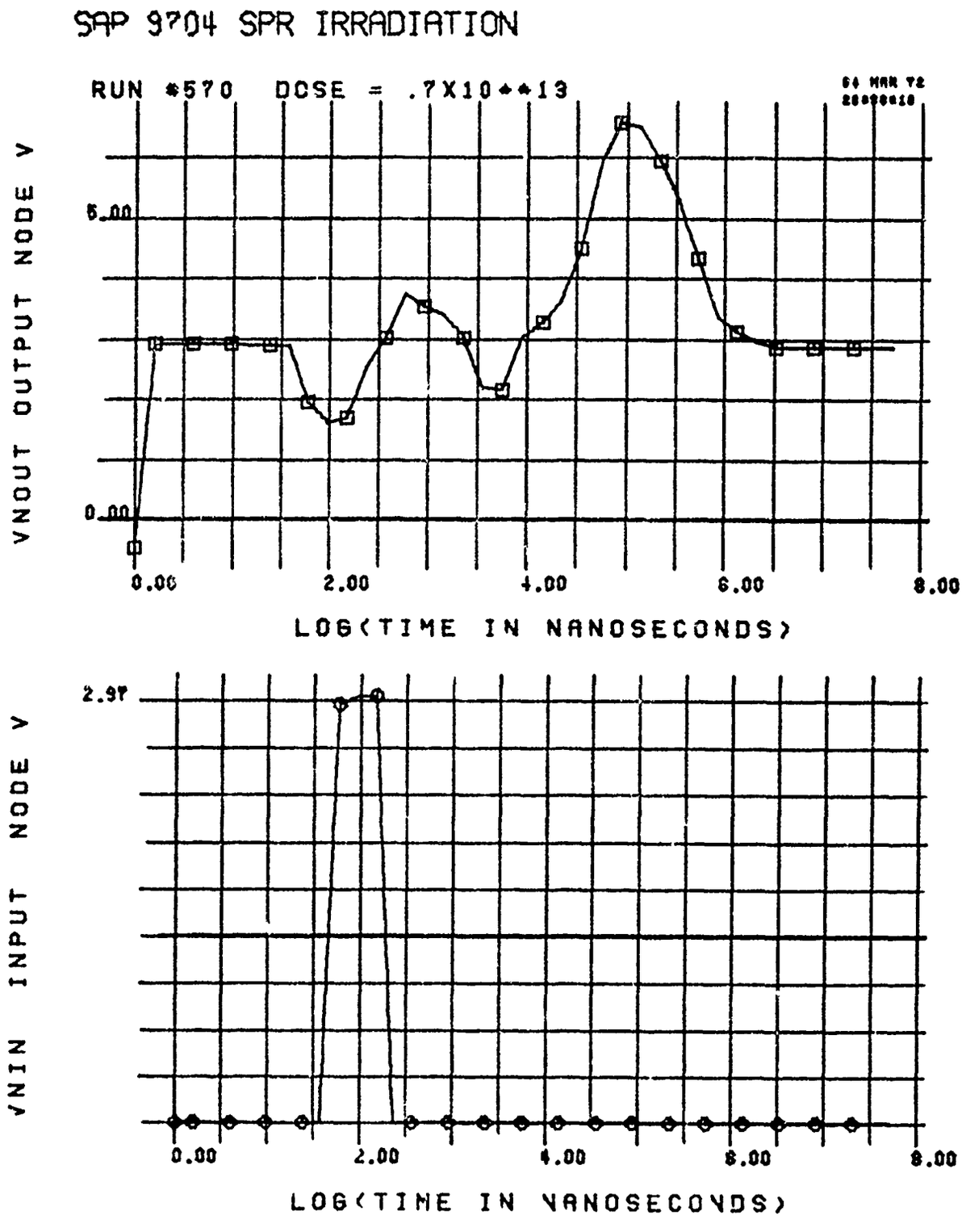


Figure 70. Second SAP Simulation of 9704 Neutron Response with Electrical Pulse. Reducing Value of XHIGH Stabilized Convolution Process.

- T_e Figure 26 9704 Voltage Response Surface,
- $T_{\varphi NV}$ Figure 33 9704 SPR Voltage-Neutron Radiation Surface,
- $T_{\varphi NC}$ Figure 36 9704 SPR Current-Neutron Radiation Surface, and
- $T_{\varphi NV}$ Figure 23 741 SPR Voltage-Neutron Radiation Surface.

The latter surface was being used by DAMAGE to calculate the permanent degradation caused by the shot.

The rather interesting item of interest of the result shown in Figure 70 is the prediction that the output voltage rises above the supply voltage of 5 v to a value more than 6 v. Rechecking the Polaroid pictures taken during the experimental bursts at the SPR showed that this was indeed true, and the calculated value agreed very well with that observed.

The results of higher neutron radiation level are given in Figure 71, for the case of a simultaneous low electrical input state. The load again for the calculation is a 500-ohm resistor. The dominant term in the output voltage is the photocurrent from the radiation current transfer function surface, Figure 36. The radiation voltage term, the curve with small triangles, did not seem to have as much effect on the output as might have been expected. This might have arisen due to the manner in which the degradation effect was being handled by DAMAGE and MAIN.

The case of a high electrical input on the gate, along with a high level SPR burst is shown in Figure 72. The first dip and peak seem to be spurious, perhaps due to the large time steps overweighing the convolution process. It might be wise to keep in mind that the convolution calculation is essentially the approximation to an integral, and when the differential time step size becomes comparable or larger than the length of the surface axis being integrated, one has to ask just how far such a concept can be stretched. Our approach in this particular run was to test on VIN, the gate input voltage, and DT, the time step interval. For time steps where successive values of VIN are the same, and DT is more than some large fraction of XHIGH, the surface length, then the output was calculated as simply the surface value itself evaluated at VIN and XHIGH Thus, the output can be returned by one look up on the surface. Evidently our coding was imperfect on this run, so that further effort is needed to properly develop the response by such a procedure.

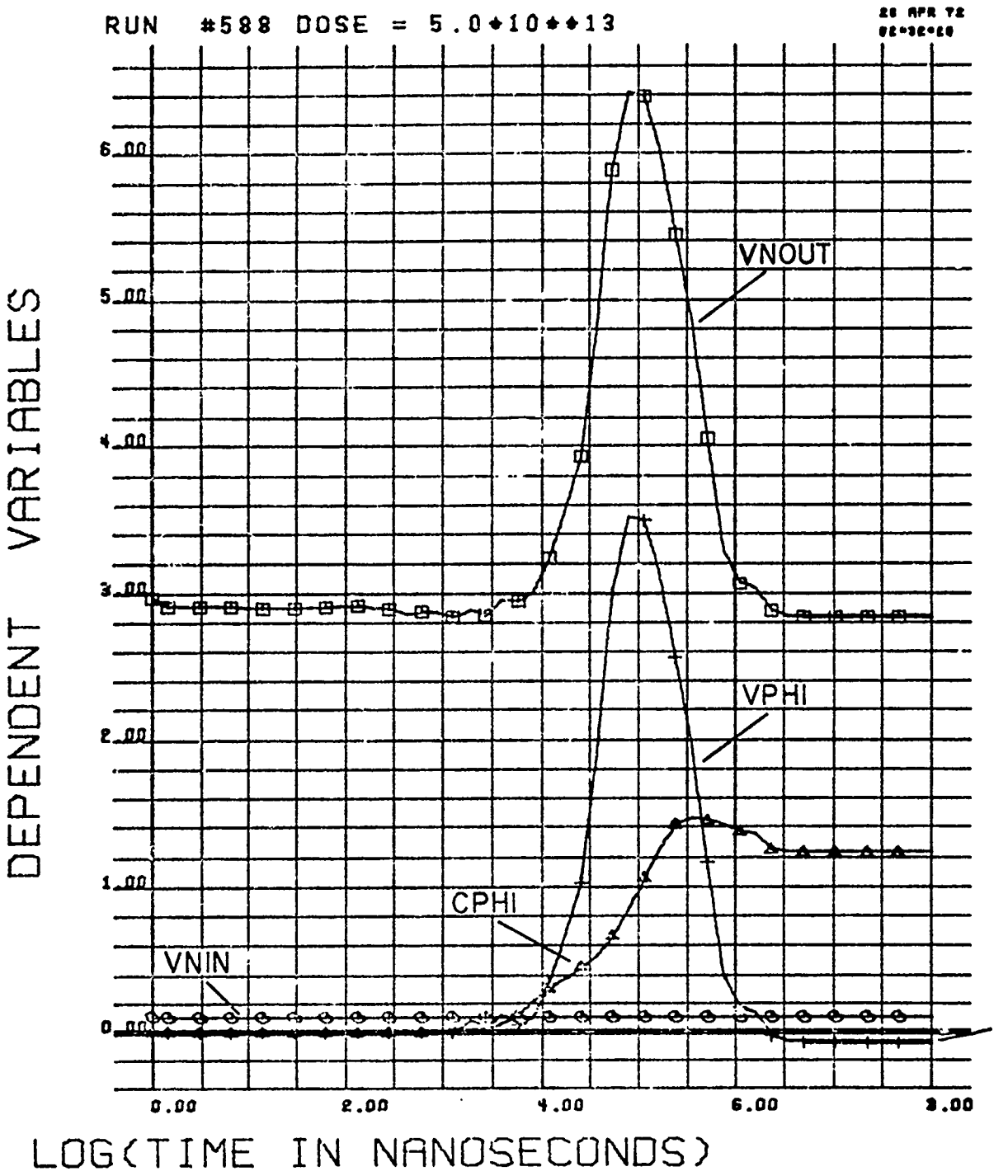


Figure 71. SAP Simulation of 9704 Response with Low State Electrical Input and High Dose SPR Neutron Radiation of 5.0×10^{13}.

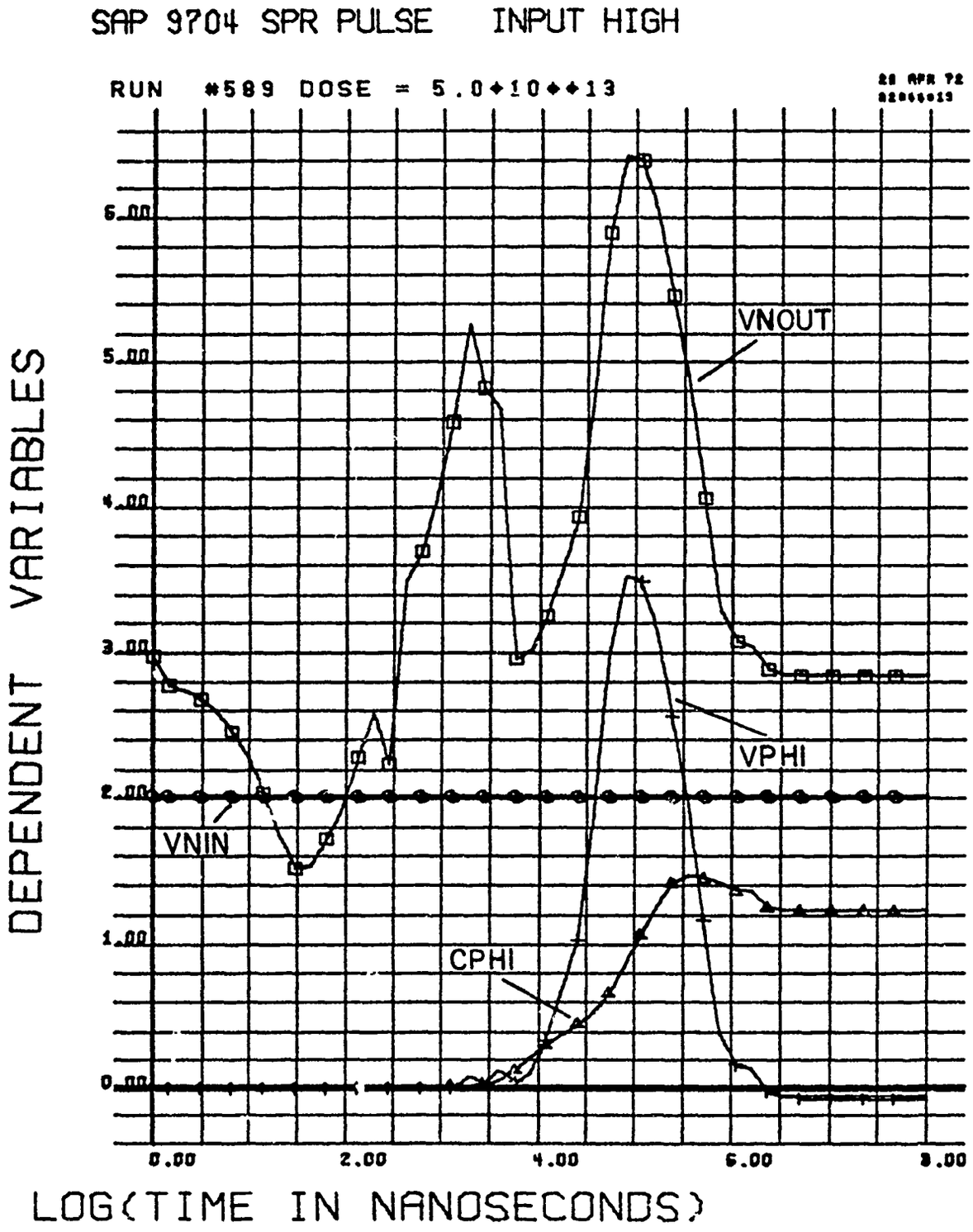


Figure 72. SAP Simulation of 9704 Response with High State Electrical Input and High Dose SPR Neutron Radiation of 5.0×10^{13}.

The last figure in the series, Figure 73, shows the calculation of the degradation of the device due to the neutron shot. This is evidenced by the fact that after the neutron burst there is no electrical output due to the turn on of an electrical input pulse at a time of 10 ms, corresponding to log(time) = 7 along the plot. For convenience, the value of the Function DAMAGE as calculated during the run is also plotted on Figure 73. This should only be regarded as demonstrating a concept, rather than being actually valid for the 9704. The damage was calculated by moving out along an isochronal of the radiation-voltage transfer function of the 741, which is certainly not a hardened, dielectrically isolated device. The dosage integration and evaluation of the surface z coordinate are handled by DAMAGE, TSURF, and SURFB. The value of DAMAGE is then used as a multiplier in MAIN to destroy the gain.

It appears then that reasonable success can be obtained with a computer based strategy which generates the system responses by retrieving the dynamical information by convolution and interpolation simultaneously on a number of multidimensional surfaces. The results presented in this section are the first attempted by such a strategy to calculate the effects of radiation on electrical devices. The computational characteristics are reasonably good. The execution time for run 590, the SPR simulation with delayed voltage pulse of Figure 73, was only 5.959 seconds for 50 time steps despite the fact that four surfaces were being processed during the calculation. While the effort expended in this program was only able to scratch the surface so to speak, the results are not discouraging.

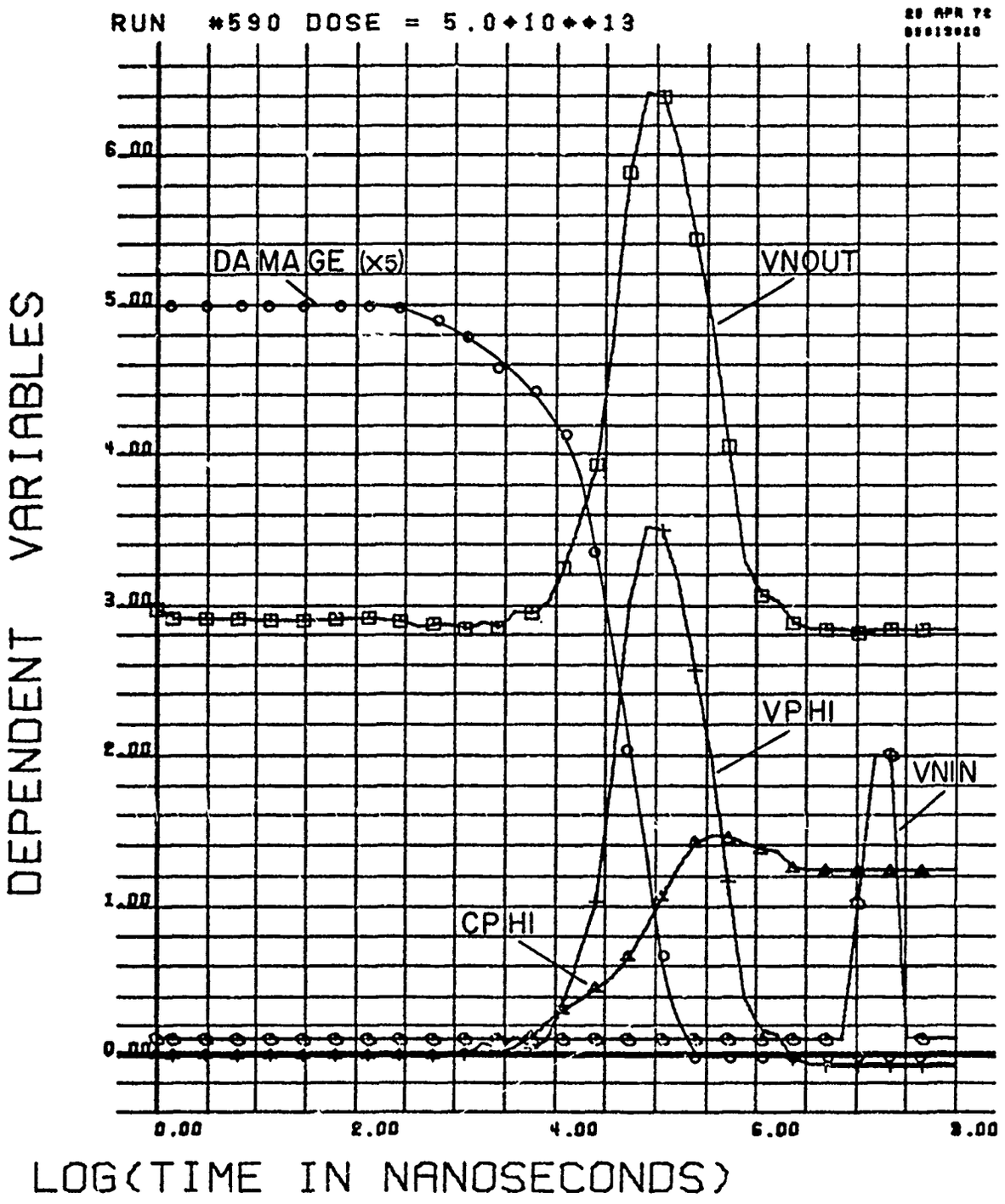


Figure 73. SAP Simulation of 9704 Response to SPR Neutron Pulse and Delayed Electrical Pulse. Absence of Response to Latter is due to DAMAGE Degradation Calculation Using 741 TPHIVN Surface of Figure 23.

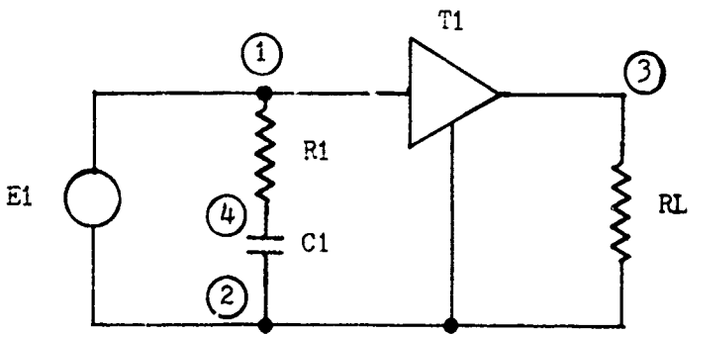
SECTION VII

MERGING SAP WITH SCEPTRE

In this section, the procedures are given by which the bivariable propagation program SAP is used with the circuit analysis program SCEPTRE. SCEPTRE was developed by AFWL under contracts AF29(601)-6489, AF29(601)-7852, F29601-67-C-0049, F29601-68-C-0117, and F29601-70-C-0038. User manuals are available from AFWL describing job deck makeups. The version of SCEPTRE which we used is an IBM 360 version modified by University Computing Company (UCC) to run on the UNIVAC 1108. This UCC version runs entirely from drum files and permits execution times typically of about 30 to 40 seconds for both Phase I and Phase II of SCEPTRE, for the cases described in the subsections below.

1. CIRCUIT MODEL

Because the surfaces contain the detailed performance information of the device, the equivalent circuit or model required to couple in with SCEPTRE is relatively simple, as shown in the sketch below.



The circuit description for SCEPTRE was:

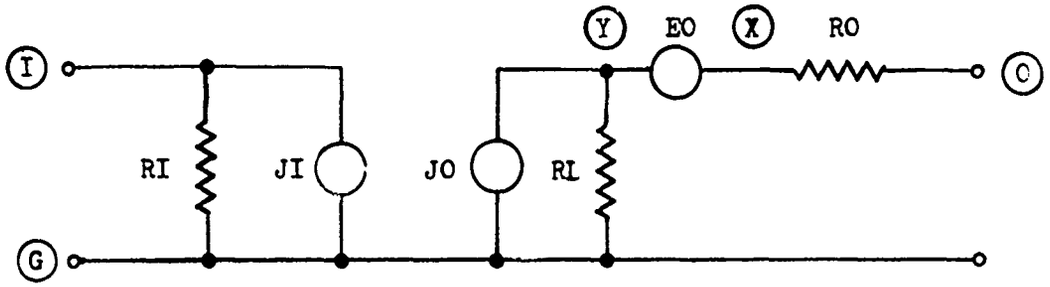
```
ELEMENTS

  E1,1-2 = FVOLT2(TIME)
  R1,1-4 = 50.0
  C1,4-2 = 1.E+10
  T1,1-3-2 = MODEL 741A (TEMP)
  RL,3-2 = 2.0
```

FVOLT2(TIME) is a function subprogram which is a modified version of VOLTIM and calculates the voltage forcing function E1 at each time step as SIMTR, the transient simulation routine written during SCEPTRE phase I, calls FVOLT2. The R1, C1 circuit on the input was mandatory simply to cause SCEPTRE to find time dependent state variables in the simulation. Otherwise the integration routines in SCEPTRE force a dummy return on all but the initialization pass, and no action is taken on subsequent time steps by SIMTR.

The model description for the 741 used was:

```
MODEL DESCRIPTION
 MODEL 741A  (TEMP) (I-O-G)
 ELEMENTS
   RI, I-G = 500.
   JI, I - G = 0
   RO, O-X = 0.1
   RL, Y-G = 500.
   JO, Y-G = FOJ741(TIME,VJI,IRI,PJ1)
   EO, X-Y = FOV741(TIME,VJI,IRI,PJ1)
DEFINED PARAMETERS
   PJ1 = 1
```

The circuit configuration corresponding to this description is:



The function subprograms FOJ741 and FOV741 are small interfacing routines that pick up the input information from SCEPTRE, transfer it to SAP by a call to MAIN2, and are given back the output voltage and current to pass back to SIMTR in SCEPTRE. The listings of these routines are given in Figure 74. The purpose of the defined parameter in the model PJ1, is simply to identify a block number which SAP can use

```
      @ ELT FOV741,1,720130, 62163    , 1

000001                  FUNCTION FOV741(TIME,VIN,CIN,JTAG)
000002                  COMMON/VCOUT/VOUT,COUT
000003                  JBLOCK = JTAG
000004                  CALL MAIN2(VIN,CIN,VOUTPT,COUTPT,JBLOCK,TIME)
000005                  VOUT = VOUTPT
000006                  COUT = COUTP
000007                  FOV741 = VOUT
000008                  RETURN
000009                  END
```

```
      @ ELT FOJ741,1,720130, 62164    , 1

C00001                  FUNCTION FOJ741(TIME,VIN,CIN,JBLOCK)
000002                  COMMON/VCOUT/VOUT,COUT
000003                  FOJ741 = COUT
000004                  RETURN
000005                  END
```

Figure 74. F O V 7 4 1 and F O J 7 4 1 Listings

to tag the 741 block. The resistance RL in parallel with JO is needed to make SCEPTRE include the voltage generator EO in calculating the output, otherwise SCEPTRE Phase One deletes EO in writing the circuit equations.

2. PROGRAM MAKE-UP USED WITH SCEPTRE

Because of the limitations of the core size available on the UNIVAC 1108 (65K decimal) when SCEPTRE Phase Two is resident, most of the unnecessary programs were deleted. These were primarily the many plot packages and subroutines. Some functions are performed by SCEPTRE that were done by routines in SAP, and so the latter were redundant. An example of the latter is the iteration routine DRIVER, since SCEPTRE already contains iteration packages. Further, the time step itself is generated as a normal process in SCEPTRE hence those sections of VOLTIM which generated the time stepping could be deleted.

The additional routines which were written to work with SCEPTRE are:

MAIN2 - cut version of MAIN

FVOLT2 - cut version of VOLTIM, creates voltage waveform

RADGN2 - RADGEN altered for call compatability as well as the the interface function subprograms FOJ741 and FOV741 given earlier. By deleting the plot routines, and cutting back the size of the XYZ common block which contains the surface files, all of the program code fit into about 7K decimal, and all of the data into about 10K decimal. This was small enough to be accomodated in core together with the UCC new version of SCEPTRE during Phase Two. The listings of these new routines, MAIN2, FVOLT2 and RADGN2, are given in Figures 75, 76, and 77.

Initially we attempted to adapt the United Aircraft version of SCEPTRE provided by AFWL. However the executive EXEC II on the Palo Alto Univac 1108 of UCC differed sufficiently to render the UA system routines inoperative. Similar problems arose with the tape obtained from Lockheed Missile and Space Company (LMSC) since the SLEUTH routines were available only in binary rather than symbolic form. Thus the approach we followed was to try and work with the UCC drum version of SCEPTRE despite the fact that UCC in Dallas refused to release the symbolics to the local UCC staff in Palo Alto. Thus when drum assignments had to be set to match our drum file designations for the surfaces, many phone calls were necessary between Palo Alto and Dallas to accomplish the most elementary tasks. Eventually the necessary

```
@ ELT FVOLT2,1,720302, 50408    , 1

000001                FUNCTION FVOLT2(TIN)
000002                INCLUDE TIME.LIST
000003                DIMENSION V(12), T(12)
000004                DIMENSION TUNIT(3), TSCALE(3)
000005                INTEGER OPTION,OPTLIN,OPTLOG,TUNIT,UNIT
000006                LOGICAL INITAL
000007                DATA INITAL/.TRUE./
000008                DATA IN,IT/5,6/
000009                DATA NANSEC/6HNANO S/,MICSEC/6HMICROS/,MILSEC/6HMILLIS/
000010                DATA OPTLOG/6HLOG   /,OPTLIN/6HLINEAR/
000011          C
000012                IF(.NOT.INITAL) GO TO 50
000013                INITAL = .FALSE.
000014                ILO = 1
000015                MODULO = 0
000016                OLDTIM = -.001
000017                OLDLOG = 0.0
000018                TRADLG = 0.0
000019                READ (IN,10)IOPT
000020              10 FORMAT(I3)
000021                 WRITE (IT,17)IOPT
000022              17 FORMAT(24H0FORCING FUNCTION OPTION =,I3)
000023                 GO TO (18,30), IOPT
000024              18 READ (IN,12)A,FREQ
000025              12 FORMAT(2(E15.8,5X))
000026                 WRITE (IT,19)A,FREQ
000027              19 FORMAT(3H0A=E15.8,5X,6H FREQ=,E15.8)
000028                 OMEGA = 2.0*3.141592654*FREQ
000029                 GO TO 40
000030              30 READ(IN,10) NSTEPS
000031                 WRITE(IT,31) NSTEPS
000032              31 FORMAT(//69H A PIECEWISE LINEAR FORCE FUNCTION IS USED WITH THE NU
000033                1MBER OF STEPS = ,I3,/ 31H  FUNCTION      TIME       UNIT  )
000034                 DO  36  I = 1, NSTEPS
000035                 READ(IN,34)  V(I),T(I), UNIT
000036                 WRITE(IT,35) V(I),T(I), UNIT
000037              34 FORMAT(2E12.8,A6)
000038              35 FORMAT(2X,2G12.4,A6)
000039                 IF(UNIT.EQ.NANSEC) TSC = 1.0
000040                 IF(UNIT.EQ.MICSEC) TSC = 1.0E+3
000041                 IF(UNIT.EQ.MILSEC) TSC = 1.0E+6
000042                 IF(UNIT.NE.NANSEC.AND.UNIT.NE.MICSEC.AND.UNIT.NE.MILSEC)
000043                1 WRITE(IT,38)
000044              36 T(I) = T(I) * TSC
000045              38 FORMAT(5X, 50H THE UNIT MULTIPLIER IS NOT CORRECT FOR THE TIME. )
000046                 NSTEP1 = NSTEPS - 1
000047              40  READ(IN,41) ISTART,TUNIT(1), ISTOP, TUNIT(2), IRADTM, TUNIT(3),
000048                1MMAX, OPTION
000049              41 FORMAT(5X,3(I6,1X,A6,2X),5X,I5,5X,A6)
000050                 WRITE(IT,41)ISTART,TUNIT(1), ISTOP, TUNIT(2), IRADTM, TUNIT(3),
000051                1MMAX, OPTION
000052                 DO  42  K = 1,3
000053                 IF (TUNIT(K) .EQ. NANSEC) TSCALE(K) = 1.0
000054                 IF (TUNIT(K) .EQ. MICSEC) TSCALE(K) = 1.0E+3
000055                 IF (TUNIT(K) .EQ. MILSEC) TSCALE(K) = 1.0E+6
000056                 IF(TUNIT(K).NE.NANSEC.AND.TUNIT(K).NE.MICSEC.AND.TUNIT(K).NE.MILSE
000057                1C) WRITE(IT,38)
000058              42 CONTINUE
```

Figure 75a. F V O L T 2 Listing

```
000059                TSTART = ISTART * TSCALE(1)
000060                TSTART = AMAX1(TSTART,1.)
000061                TSTOP  = ISTOP  * TSCALE(2)
000062                RADTIM = IRADTM * TSCALE(3)
000063                IF (OPTION .EQ. OPTLIN) MODE = 1
000064                IF (OPTION .EQ. OPTLOG) MODE = 2
000065                WRITE (IT,46) OPTION
000066                IF(OPTION.NE.OPTLIN.AND.OPTION.NE.OPTLOG) STOP
000067             46 FORMAT(10X,A6,21H TIME STEPS ARE USED.  / )
000068                GO TO (47,48), MODE
000069             47 A1 = TSTART
000070                A2 = (TSTOP - TSTART) / (MMAX - 1)
000071                GO TO 50
000072             48 A1 = ALOG10(TSTART)
000073                A2 = (ALOG10(TSTOP/TSTART))/(MMAX - 1)
000074          C
000075          C     ENTRY POINT ON ALL BUT FIRST CARD READ OPERATION
000076          C     MODE = 1 CORRESPONDS TO  A  LINEAR  TIME BASE.
000077          C     MODE = 2 CORRESPONDS TO LOGARITHMIC TIME BASE.
000078          C
000079             50 TT = TIN
000080                IF(.NOT.(TT.GT.OLDTIM)) RETURN
000081                M = M + 1
000082                MPRIME = M - MODULO * LMAX
000083                IF(MPRIME.EQ.LMAX) MODULO = MODULO + 1
000084                TIME(MPRIME,1) = TT
000085                TIME(MPRIME,2) = ALOG10(AMAX1(TT,1.))
000086                DT = TIME(MPRIME,1) - OLDTIM
000087                DLOGT = TIME(MPRIME,2) - OLDLOG
000088                OLDTIM = TIME(MPRIME,1)
000089                OLDLOG = TIME(MPRIME,2)
000090                DTL(MPRIME,1) = DT
000091                DTL(MPRIME,2) = DLOGT
000092                TRAD = TIME(MPRIME,1) - RADTIM
000093                TRADLG = ALOG10(AMAX1(TRAD,1.))
000094                IHI = MPRIME
000095                IF(MODULO.GT.0) IHI = LMAX
000096                DO  56  I = 1, IHI
000097                TL(I,1) = TIME(MPRIME,1) - TIME(I,1)
000098             56 TL(I,2) = TIME(MPRIME,2) - TIME(I,2)
000099          C
000100             58 GO TO(59,60), IOPT
000101             59 FVOLT2 = A* SIN(OMEGA*TIME(MPRIME,1))
000102                RETURN
000103             60 DO  70  I = ILO, NSTEP1
000104                IF((TIME(MPRIME,1).GT.T(I).OR..NOT.TIME(MPRIME,1).LT.T(I)).AND.
000105               1 TIME(MPRIME,1).LT. T(I+1))  GO TO 80
000106             70 CONTINUE
000107                I = I - 1
000108             80 ILO = I
000109                FVOLT2 =(V(I+1)-V(I))*(TIME(MPRIME,1)-T(I))/(T(I+1)-T(I)) + V(I)
000110            200 RETURN
000111                END
```

Figure 75b. F V O L T 2 Listing (cont.)

```
* FLT MAIN2,1,720310,  8376     , 1

000001                SUBROUTINE MAIN2(VINPUT,CINPUT,VOUTPT,COUTPT,JBLOCK,T)
000002                INCLUDE SAP,LIST
000003                INCLUDE TIME,LIST
000004                INCLUDE XYZ,LIST
000005                COMMON / DEBUG / IDEBUG
000006                LOGICAL IDEBUG
000007                DIMENSION NIN(IX),NOUT(IX),LBLOCK(IX,IX),ISURF(NSURF),LTIME(2)
000008               1,JPARAL(IX),FACTOR(IX),CNOUT(IX),VNOUT(IX),CNIN(IX),VNIN(IX)
000009               2,LMEX(IX)
000010                LOGICAL IRADX,IRADN,INITAL,ISYM,ISYML
000011          C     ISYM = .TRUE. IMPLIES SURFACE IS SYMMETRIC WITH RESPECT TO Y = 0.
000012          C     KMAX = MAXIMUM NUMBER OF ITERATIONS.
000013                DATA EPSLN2/.01/,EPSLN3/1.0E-8/,IN/5/,IT/6/,KMAX/20/
000014                DATA LIMITG/10/, VTEST/.05/, CTEST/.05/, M/0/
000015                DATA INITAL/.TRUE./,IDEBUG/.TRUE./,IXBASE/0/,IYBASE/0/,IZBASE/0/
000016                DATA NOMORE/6HNOMORE/, TOLD/-.001/
000017                DATA LTIME(1)/0/, FACTOR(1)/0./
000018                DATA TIN/1.E-20/, SMALL/1.E-12/, SAP2/4HSAP2/, STAR/4H****/
000019          C
000020          C
000021          C
000022                IF(.NOT.INITAL) GO TO 80
000023          ...   INITAL = .FALSE.
000024          C
000025          C     IF THE ROUTINE DAMAGE IS CALLED UPON, THE SURFACE ZVN741,
000026          C     MUST BE READ IN BY MAIN. THIS CORRESPONDS TO LSURF = 5.
000027          C
000028                WRITE(IT,1) STAR,SAP2,STAR,SAP2,STAR,SAP2,STAR,SAP2,STAR,SAP2,STAR
000029              1 FORMAT(1H1, //,10X,5(A4,4X,A4,4X),A4  //)
000030                READ(IN,2) (ISURF(L),L=1,NSURF)
000031              2 FORMAT(12I5)
000032                WRITE(IT,3) (L,ISURF(L),L=1,NSURF)
000033              3 FORMAT(/ 2X,8(3X, 6HISURF(,I2,4H) = ,I1) /)
000034          C
000035          CALLING INPUT DATA FROM SUBROUTINE DATA.
000036                CALL DATA
000037          C
000038          CALLING SURFACE INFORMATION FROM DRUM FILES.
000039                DO  13  L = 1, NSURF
000040                IF(ISURF(L).EQ.0)  GO TO 13
000041          C     INPUT = L + 17
000042                INPUT = IN
000043                READ(INPUT,4) XLO,XHI,YLO,YHI,IXDIMN,IYDIMN,LL,ISYML,(SCALE(L,J)
000044               1,J=1,3)
000045              4 FORMAT(4E8.4,3I4,L6,3E10.3)
000046                IXDIM(L) = IXDIMN
000047                IYDIM(L) = IYDIMN
000048                ISYM(L) = ISYML
000049                XLOW(L) = .9999998 * XLO
000050                YLOW(L) = .9999998 * YLO
000051                XHIGH(L) = 1.0000002 * XHI
000052                YHIGH(L) = 1.0000002 * YHI
000053                XDELTA = (XHIGH(L)-XLOW(L))/(IXDIM(L)-1)
000054                YDELTA = (YHIGH(L)-YLOW(L))/(IYDIM(L)-1)
000055                WRITE(IT,5) L,XLO,XHI,YLO,YHI,XDELTA,YDELTA,IXDIMN,IYDIMN,LL,ISYML
000056               1,(L,J,SCALE(L,J),J=1,3)
000057              5 FORMAT(/13H FOR SURFACE ,I2,/4H  XLO =,G11.4,7H,  XHI =,G11.4,7H,  YL
000058               10 =,G11.4,7H,  YHI =,G11.4,10H,  XDELTA =,G11.4,10H,  YDELTA =,G11.4,
```

Figure 76a. M A I N 2 Listing

```
000059                2/9H  IXDIM =,I3,9H, IYDIM =,I3,5H, L =,I2,9H, ISYM = ,L1,5X,3(8H
000060               3SCALE(,I1,1H,,I1,3H) =,G10.2)/)
000061              6 FORMAT(/ 10X,8HIXBASE =,I3,5X,8HIYBASE = ,I3,5X,8HIZBASE =,I5 /)
000062          C
000063          CREATING X AND Y ARRAYS FROM INPUTTED INFORMATION.
000064          C
000065                IPONTR(L,1) = IXBASE + 1
000066              8 FORMAT(/ 5X,3(7HIPONTR(,I2,1H,,I2,3H) =,I5,1H,5X)/)
000067                DO  9  I = 1, IXDIMN
000068              9 X(I + IXBASE) = XLO + (I-1)*XDELTA
000069                IXBASE = IXBASE + IXDIMN
000070                IPONTR(L,2) = IYBASE + 1
000071                DO  10  J = 1, IYDIMN
000072             10 Y(J+IYBASE) = YLO + (J-1)*YDELTA
000073                IYBASE = IYBASE + IYDIMN
000074                IPONTR(L,3) = IZBASE + 1
000075                WRITE(IT,    8) (L,J,IPONTR(L,J),J=1,3)
000076                MINC = IXDIMN * IYDIMN
000077                MINC2 = MINC + MINC
000078                JHI = IYDIMN - 1
000079                DO  12  I = 1, IXDIMN
000080                DO  12  J = 1, JHI, 2
000081                MS1 = I + (J-1)*IXDIMN + IZBASE
000082                MS2 = MS1 + IXDIMN
000083                ML1 = MS1 + MINC2
000084                ML2 = MS2 + MINC2
000085                READ(INPUT,11)(Z(KK),KK=MS1,ML1,MINC),(Z(KKK),KKK=MS2,ML2,MINC)
000086             11 FORMAT(6F13.7)
000087             12 CONTINUE
000088                IZBASE = IZBASE + 3*MINC
000089             13 CONTINUE
000090                WRITE(IT,6) IXBASE,IYBASE,IZBASE
000091                IF(IXBASE.GT.IXLIM.OR.IYBASE.GT.IYLIM.OR.IZBASE.GT.IZLIM) STOP
000092          C
000093                DAMAGX = 1.0
000094                DAMAGN = 1.0
000095          C
000096                WRITE(IT,20)
000097             20 FORMAT(41H INPUT THE VALUE OF JMAX, USE FORMAT I3.  /)
000098                READ(IN,22) JMAX
000099             22 FORMAT(I3)
000100                WRITE(IT,24) JMAX
000101             24 FORMAT(33H THE VALUE OF JMAX AS READ IN IS , I3 /)
000102                WRITE(IT,30)
000103             30 FORMAT(71H INPUT THE VALUES IN SEQUENCE OF J, CONFIG,NIN,NOUT,R,C,
000104               1 L, 4I3,3F12.4     /)
000105                DO  32  J = 1, JMAX
000106                READ(IN,34) I, ITABLE(J,1)        ,NIN(J),NOUT(J),R(J),C(J),FL(J)
000107             32 WRITE(IT,34)I, ITABLE(J,1)        ,NIN(J),NOUT(J),R(J),C(J),FL(J)
000108                CALL SETUP(   NIN,NOUT,LBLOCK,JMAX,NMAX,JPARAL,LMEX)
000109             33 CONTINUE
000110             34 FORMAT(4I3, 3F12.4)
000111          C
000112          C     IF INKALL .NE. 1, PRINTING IS SUPPRESSED, EXCEPT FOR EVERY MMODTH
000113          C     TIME STEP.
000114                WRITE(IT,41)
000115             41 FORMAT(41H INPUT THE VALUE OF INKALL AND MMOD, 2I3. /)
000116                READ(IN,42) INKALL,MMOD
000117             42 FORMAT(2I3)
000118                WRITE(IT,44) INKALL,MMOD
```

Figure 76b. M A I N 2 Listing (cont.)

```
000119          44 FORMAT( 9H INKALL =,I2,10H,   MMOD =,I3     /)
000120        C
000121             READ(IN,46) EPSLON
000122          46 FORMAT(F10.6)
000123             WRITE(IT,48) EPSLON
000124          48 FORMAT(32H THE ITERATION CRITERIA,EPSLON =, G14.8 /)
000125        C
000126             KROSS = 1
000127          75 CALL RADGN2(0,PHI,IRADX,IRADN)
000128        C
000129        C     NORMAL ENTRY ON ALL BUT INITIAL PASS.
000130        C
000131          80 CONTINUE
000132             MTRUN = M/MMOD
000133             MODM = MTRUN*MMOD/M
000134             J = JBLOCK
000135             N = NIN(J)
000136             CALL RADGN2(1,PHI,IRADX,IRADN)
000137        C
000138             IF(IRADX.AND.PHI(1).GT.0.) PHIXL = ALOG10(PHI(1))
000139             IF(IRADN.AND.PHI(2).GT.0.) PHINL = ALOG10(PHI(2))
000140        C
000141             VNIN(N) = VINPUT
000142             CNIN(N) = CINPUT
000143             IF(ABS(VNIN(N)).LT.TINY) VNIN(N) = SMALL
000144             IF(ABS(CNIN(N)).LT.TINY) CNIN(N) = SMALL
000145             CIN(J,1) = CNIN(N)
000146             VIN(J,1) = VNIN(N)
000147             ITERAT = 1
000148             ITRSAV = ITERAT
000149             NITER = 0
000150        C
000151         207 NITER = NITER + 1
000152             ITERAT = ITRSAV * NITER
000153         209 VOLD = VOUT(J,1)
000154             COLD = COUT(J,1)
000155             IF(ABS(VOLD).LT.TINY) VOLD = SMALL
000156             IF(ABS(VOLD).LT.TINY) VOLD = SMALL
000157         210 VOUT(J,1) = VIN(J,1) * FE(J)
000158             COUT(J,1) = CIN(J,1) * FI(J)
000159         224 VTST = ABS ( 1.0 - VOUT(J,1)/VOLD )
000160             CTST = ABS ( 1.0 - COUT(J,1)/COLD )
000161             IF(.NOT.(ABS(VOLD).GT.0.)) VTST = 0.
000162             IF(.NOT.(ABS(COLD).GT.0.)) CTST = 0.
000163         226 IF ((VTST .GT. VTEST  .OR.  CTST .GT. CTEST) .AND. NITER.LE.LIMITQ
000164            1) GO TO 207
000165             ITERAT = ITRSAV
000166         230 IF ( ITERAT .GT. 1 ) GO TO 231
000167             IF(IRADX) VOUT(J,3) =              PHIXL * FEPHI(J,1)
000168             IF(IRADN) VOUT(J,3) =              PHINL * FEPHI(J,2)
000169             IF(IRADX) COUT(J,3) =              PHIXL * FIPHI(J,1)
000170             IF(IRADN) COUT(J,3) =              PHINL * FIPHI(J,2)
000171             IF(IRADX) DAMAGX = DAMAGE(J,1)
000172             IF(IRADN) DAMAGN = DAMAGE(J,2)
000173             DAMAGT = DAMAGX * DAMAGN
000174             IF(.NOT.(IRADX.OR.IRADN)) GO TO 231
000175             VOUT(J,1) = VOUT(J,1)*DAMAGT + VOUT(J,3)
000176             COUT(J,1) = COUT(J,1)*DAMAGT + COUT(J,3)
000177         231 CONTINUE
000178         232 VNOUT(N) = VOUT(J,1)
```

Figure 76c. M A I N 2 Listing (cont.)

```
000179                CNOUT(N) = COUT(J,1)
000180                VOUTPT = VOUT(J,1)
000181                COUTPT = COUT(J,1)
000182          C
000183            440 IF(.NOT.(INKALL.EQ.1.OR.MODM.EQ.1))  GO TO 450
000184                WRITE(IT,441)
000185            441 FORMAT(// 128H  J     VIN(J)        CIN(J)      VOUT(J,1)     COUT(J,1
000186               1)      VDIFF      CDIFF      VOUT(J,2)     COUT(J,2)     VOUT(J,3)     C
000187               2OUT(J,3)    )
000188                JLO = J
000189                JHI = J
000190            444 DO  445  J = JLO, JHI
000191                VDIFF = VIN(J,1)-VOUT(J,1)
000192                CDIFF = CIN(J,1)-COUT(J,1)
000193            445 WRITE(IT,446)J,VIN(J,1),CIN(J,1),VOUT(J,1),COUT(J,1),VDIFF,CDIFF
000194               1,VOUT(J,2),COUT(J,2),VOUT(J,3),COUT(J,3)
000195            446 FORMAT(I3,10(1X,G11.3))
000196            450 DO  480  J = JLO, JHI
000197                DO  460  JIG = 2, JT
000198                         JOG = JT - JIG + 2
000199                   VIN(J,JOG) = VIN(J,JOG-1)
000200                   CIN(J,JOG) = CIN(J,JOG-1)
000201                VINTGL(J,JOG) = VINTGL(J,JOG-1)
000202                CINTGL(J,JOG) = CINTGL(J,JOG-1)
000203            460 CONTINUE
000204                DO  470  JIG = 2, JD
000205                         JOG = JD - JIG + 2
000206                VINDT1(J,JOG) = VINDT1(J,JOG-1)
000207                CINDT1(J,JOG) = CINDT1(J,JOG-1)
000208            470 CONTINUE
000209            480 CONTINUE
000210                RETURN
000211                END
```

Figure 76d. M A I N 2 Listing (cont.)

```
* ELT RADGN2,1,720302, 50500    , 1

000001                SUBROUTINE RADGN2 (N,PHI,IRADX,IRADN)
000002                INCLUDE TIME,LIST
000003                DIMENSION RHO1(25),RHO2(25),T1(25),T2(25),PHI(2)
000004                DIMENSION ITYPE1(2),ITYPE2(2),NAME1(2),NAME2(2),IWEIBL(2),
000005               1IGAUSS(2),IPIECE(2),IXRAY(2),NEUTRN(2)
000006                LOGICAL IRADX1,IRADN1,IRADX2,IRADN2,IRADX,IRADN,KONVOL
000007                DATA IN,IT/5,6/
000008                DATA IWEIBL(1)/6HWEIBUL/,IWEIBL(2)/6HL      /,IGAUSS(1)/6HGAUSSI/,
000009               1      IGAUSS(2)/6HAN    /,IXRAY(1)/6HXRAY  /,IXRAY(2)/6H      /,
000010               2      NEUTRN(1)/6HNEUTRO/,NEUTRN(2)/6HN     /,IPIECE(1)/6HPIECEW/,
000011               3      IPIECE(2)/6HISE   /,IBLANK/6H      /
000012                DATA IFXR/6HFXR   /,ISPR/6HSPR   /
000013          C
000014          C
000015          C THE DISTRIBUTION FORCING FUNCTIONS ARE CALCULATED BY USING THE
000016          C FOLLOWING STATEMENT FUNCTIONS.
000017                PWEIBL(TYME,ALPHA,BETA,GAMMA) = (BETA * ALPHA ** (-BETA)*(TYME -
000018               1  GAMMA) ** (BETA-1))** (((TYME-GAMMA)/ALPHA) ** BETA)
000019                PGAUSS(TYME,A,TAU,SIGMA)=(A/(SIGMA * (2*3.14159) ** 0.5))**
000020               1  (( TYME - TAU) ** 2 / (2 * SIGMA ** 2))
000021                PICWIS (RI,RIP1,TI,TIP1,PHIMAX,TYME) = ((RIP1 - RI) * (TYME - TI)
000022               1  /( TIP1 - TI ) + RI) * PHIMAX
000023          C
000024          C DATA ARE READ WHEN N = 0 .
000025          C
000026                IF (N - 1) 5, 100, 200
000027          C INITIALIZATION
000028              5 IRADX1 = .FALSE.
000029                IRADN1 = .FALSE.
000030                IRADX2 = .FALSE.
000031                IRADN2 = .FALSE.
000032                IRADX = .FALSE.
000033                IRADN = .FALSE.
000034                KONVOL(1) = .TRUE.
000035                KONVOL(2) = .TRUE.
000036                RADTIM = 0.0
000037                ILO = 1
000038                KOUNT1 = 0
000039                KOUNT2 = 0
000040                NUMBER = 0
000041          C
000042                READ(IN,10) ITYPE1(1),ITYPE1(2),NAME1(1),NAME1(2),B1,B2,B3
000043             10 FORMAT (4A6,6X,3E10.5)
000044                IF ( NAME1(1).EQ. IFXR .OR.NAME1(1).EQ.ISPR) RADTIM = B2
000045                IF (RADTIM .GT. 0.0) RADTLG = ALOG10(RADTIM)
000046                IF(ITYPE1(1).NE.IBLANK.AND.NAME1(1).NE.IFXR.AND.NAME1(1).NE.ISPR)
000047               1 NUMBER = NUMBER + 1
000048                IF (NAME1(1) .NE. IPIECE(1)) GO TO 35
000049                NSTEPS = 51
000050                WRITE (IT,15) NSTEPS
000051             15 FORMAT (6HNSTEPS = ,I3)
000052                DO  25  I = 1, NSTEPS
000053                READ(IN,20) RHO1(I),T1(I)
000054             20 FORMAT (2E10.5)
000055             25 WRITE(IT,30) I,RHO1(1),I,T1(I)
000056             30 FORMAT( 6HRHO1( ,I3,5H ) = ,G12.5,5X,4HT1( ,I3,5H ) = ,G12.5)
000057                NSTEP1 = NSTEPS - 1
000058             35 READ(IN,10) ITYPE2(1),ITYPE2(2),NAME2(1),NAME2(2),C1,C2,C3
```

Figure 77a. R A D G N 2 Listing

```
000059              IF ( NAME2(1).EQ. IFXR .OR.NAME2(1).EQ.ISPR) RADTIM = C2
000060              IF(ITYPE2(1).NE.IBLANK.AND.ITYPE1(1).NE.ITYPE2(1).AND.NAME2(1)
000061             1.NE.IFXR.AND.NAME2(1).NE.ISPR) NUMBER = NUMBER + 1
000062              IF(NAME2(1) .NE. IPIECE(1)) GO TO 60
000063              NSTEPS = C1
000064              WRITE (IT,15) NSTEPS
000065              DO  40  I = 1, NSTEPS
000066              READ(IN,20) RHO2(I), T2(I)
000067           40 WRITE(IT,30) I, RHO2(I), I, T2(I)
000068              NSTEP2 = NSTEPS - 1
000069           60 WRITE(IT,65) ITYPE1(1),ITYPE1(2),NAME1(1),NAME1(2),B1,B2,B3
000070              WRITE(IT,65) ITYPE2(1),ITYPE2(2),NAME2(1),NAME2(2),C1,C2,C3
000071           65 FORMAT(18H RADIATION TYPE = , 2A6, 5X, 15HDISTRIBUTION =
000072             1  2A6 / 5X
000073             2 32HTHE 3 RESPECTIVE PARAMETERS ARE ,3(4X,G10.5))
000074         C
000075         C
000076              IF (ITYPE1(1) .EQ. IXRAY(1)) IRADX1 = .TRUE.
000077              IF (ITYPE1(1) .EQ.NEUTRN(1)) IRADN1 = .TRUE.
000078              IF (ITYPE2(1) .EQ. IXRAY(1)) IRADX2 = .TRUE.
000079              IF (ITYPE2(1) .EQ.NEUTRN(1)) IRADN2 = .TRUE.
000080              IF (IRADX1 . OR. IRADX2) IRADX = .TRUE.
000081              IF (IRADN1 . OR. IRADN2) IRADN = .TRUE.
000082         C
000083         C THE MEANING OF THE SUBSCRIPTS ON PHI AND KONVOL ARE AS FOLLOW
000084         C   1 = X-RAY   IRRADIATION
000085         C   2 = NEUTRON IRRADIATION
000086         C
000087              IF ((NAME1(1) .EQ. IFXR .AND. ITYPE2(1) .EQ. IXRAY(1)) .OR.
000088             1    (NAME2(1) .EQ. IFXR .AND. ITYPE1(1) .EQ. IXRAY(1)) .OR.
000089             2    (NAME1(1) .EQ. ISPR .AND. ITYPE2(1) .EQ. NEUTRN(1)) .OR.
000090             3    (NAME2(1) .EQ. ISPR .AND. ITYPE1(1) .EQ. NEUTRN(1)))GO TO 900
000091              IF(NAME1(1).EQ.IFXR.OR.NAME2(1).EQ.IFXR) KONVOL(1) = .FALSE.
000092              IF(NAME1(1).EQ.ISPR.OR.NAME2(1).EQ.ISPR) KONVOL(2) = .FALSE.
000093              RETURN
000094         C WHEN N = 1, DIFFERENT FORCING FUNCTIONS ARE CALCULATED AND RETURN
000095         C THE RESPECTIVE RESULTS TO THE CALLING PROGRAM.
000096           100 NN = N
000097              TIM = TIME(MPRIME,1)
000098              K=1
000099              IF (IRADX1) GO TO 110
000100              IF (.NOT.IRADN1) GO TO 150
000101              K=2
000102           110 IF (NAME1(1) .EQ. IWEIBL(1)) PHI(K) = PWEIBL(TIM ,B1,B2,B3)
000103              IF (NAME1(1) .EQ. IGAUSS(1)) PHI(K) = PGAUSS(TIM ,B1,B2,B3)
000104              IF(NAME1(1).EQ.IFXR.OR.NAME1(1).EQ.ISPR) PHI(K) = B1
000105              IF (NAME1(1) .NE. IPIECE(1)) GO TO 150
000106              DO  125  I = ILO,NSTEP1
000107              IF((TIM.GT.T1(I).OR..NOT.TIM.LT.T1(I)).AND.TIM.LT.T1(I+1))GO TO130
000108           125 CONTINUE
000109              I = I - 1
000110           130 ILO = I
000111              IP1 = I + 1
000112              PHI(K) = PICWIS ( RHO1(I),RHO1(IP1),T1(I),T1(IP1),B2,TIM)
000113           150 L = 1
000114              DELTA = 0.0
000115              IF (IRADX2) GO TO 175
000116              IF (.NOT.IRADN2) RETURN
000117              L = 2
000118           175 IF(L.EQ.K) DELTA = 1.0
```

Figure 77b. R A D G N 2 Listing (cont.)

```
000119              IF (NAME2(I) .EQ. IWEIBL(I)) PHI(L) = PWEIBL(TIM ,C1,C2,C3)
000120             1    + DELTA * PHI(K)
000121              IF (NAME2(I) .EQ. IGAUSS(I)) PHI(L) = PGAUSS(TIM ,C1,C2,C3)
000122             1    + DELTA * PHI(K)
000123              IF(NAME2(I).EQ.IEXR.OR.NAME2(I).EQ.ISPR) PHI(L) = C1
000124              IF (NAME2(I) .NE. IPIECE(I)) GO TO 200
000125              DO 180  I = ILO,NSTEP2
000126              IF((TIM.GT.T2(I).OR..NOT.TIM.LT.T2(I)).AND.TIM.LT.T2(I+1))GO TO190
000127            180 CONTINUE
000128              I = I - 1
000129            190 ILO = I
000130              IP1 = I + 1
000131              PHI(L) = PICWIS ( RHO2(I),RHO2(IP1),T2(I),T2(IP1),C2,TIM)
000132             1    + DELTA * PHI(K)
000133            200 RETURN
000134            900 WRITE (IT,910)
000135            910 FORMAT(56H   TERMINATED BY RADGN2 DUE TO INCONSISTENT DATA CARDS.)
000136              STOP
000137              END
```

Figure 77c. R A D G N 2 Listing (cont.)

modifications were achieved with the results which will be given in a later section.

The loader or allocator on the Univac 1108 will automatically search the PCF (Program Complex File) for all necessary subroutinos required by the main program, and load them at execution time. Unnecessary routines will not be loaded. All the routines required to execute SAP starting with program MAIN were stored in a FASTRAND drum file called SAP/SAP1. This included all the plot routines. The additional routines used to execute with SCEPTRE were stored in a file called SAP/SAP2. Both files were called into the PCF for execution with SCEPTRE, and the UNIVAC allocator loaded the needed routines.

In the case of operating with the CDC 6600, it was necessary to split the program into three files:

1) routines used in execution of SAP without SCEPTRE, and consisting primarily of plot subroutines,
2) routines required only while executing SAP with SCEPTRE, and
3) routines required both in execution of SAP alone, or of SAP in conjunction with SCEPTRE.

Thus if SAP alone were to be executed, the first and last program files would be loaded; while if SAP was to be executed with SCEPTERE, the last two files would be loaded. Those original SAP routines which were altered or rewritten for SCEPTRE thus would be in the first file, while the modified versions were in the second file. The routines which were unchanged, such as FE, FI, CONVOL, TSURF, SURFB, DAMAGE, SETUP, FEPHI, etc. were in the third file.

A major problem encountered in adapting FIT3D and SAP to the CDC 6600 arose due to the difference in the manner in which the UNIVAC 1108 and the CDC 6600 treat division by zero. The UNIVAC 1108 FORTRAN V compiler of UCC sets the result of dividing by zero equal to zero. The CDC compiler sets the result equal to an "indefinite" quantity. Whenever this indefinite result is subsequently used in a calculation, the new result is set indefinite, etc., etc. The propagation of the indefinite quantity throughout the rest of the entire computation usually does not take long. If overflow occurs, a similar phenomena takes place. Thus it is mandatory to test every denominator which may conceivably go to zero during a calculation, and reset it to some acceptable small value if zero does occur.

Since the basic computational strategy of SAP involves the ratio of an output to input stimuli in the transfer function, and a zero value of the input stimuli is

perfectly acceptable, such zeroes in the denominator can and did occur. The output is usually well defined in such a situation. For example for the 741 op amp, a zero input leads to a zero output. This happens to be precisely the action taken by the UNIVAC 1108 Fortran, and so we did not experience any difficulty, due to this class of problem. However, for machines which treat the case differently, it is wise to test every possible denominator which may go to zero in order to get around the action otherwise taken by the system.

3. RESULTS CALCULATED WITH SCEPTRE

Using the Model Description and Circuit Description given above, and with Outputs and Run Controls as follows:

```
OUTPUTS
  E1, IE1, VRL, IRL, PLOT
RUN CONTROLS
  STOP TIME = 4E+7
STOP
```

SCEPTRE Phase One generated the SIMUL8 and SIMTR programs given in the listings of Figures 78 and 79.

The output voltage as calculated by SAP using the voltage response surface TE741 of Figure 20 is plotted in Figure 80. A few pages of the output listing from SAP for the run is given in Figure 81, while the output as printed by SCEPTRE is given in Figure 82. The running sums of the convolution process are printed by CONVOL in the output of Figure 81 every tenth time step. The oldest partitions occur first with a contribution to the output given under the column heading marked TEMP. The value of the surface contribution for the partitions is given in the column labeled TSURF. The running sum is added successively along the column labeled SUM. The time that has passed since the arrival of the partition is given in the column TIMER. UIN is the value of the stimulus variable for the partition. DTL is the time step interval coming in from the iteration routines in SCEPTRE. Note that these steps are alternating in size, and are different than the time step interval printed out in the SCEPTRE printout of Figure 82.

The entries printed out by SAP at each time step are the block input/output voltages and currents. Since no radiation was acting, the UT(J,3) terms are

```
   0005 P 000005 XR22D      0005 P 000013 XR55D      0004    000042 XSAVE      0004    000001 XSTOP
   0004   000040 XSTPSZ     0004   000004 XTISSS     0004    000043 XTMON      0004    000041 XTRAN
   0004   000024 XYOTMS

00101      1*          SUBROUTINE SIMTR (KWAY,KSWIT)
00103      2*          IMPLICIT REAL (A-J,L-M,O-Z), INTEGER (K,N)
00103      3*    C     SCRIPTRF/110R CIRCUIT ANALYSIS PROGRAM
00104      4*          COMMON /TAPES/NOUTTP,NTAPE,NLIBTP,NOUTP,NEDITP,NSAVTP
00105      5*          COMMON /CONTRLS/TIME,XSTOPT,XMXERT,XIR,XTISSS,XMNISS,XMXISS,XMNAIE,
00105      6*         *XMXAIE,XIC,XMERNO,XMXPAS,XMNRIE,XMARIE,XMNISO,XMXICP,XICRER,XICAER
00105      7*         *,XMXOTP,XYOTMS,XYOTMS,XICPAS,XNOPRG,XNTNDX,XNMEAD,XNOFEQ,XERT,XNRE
00105      8*         *PN,XCNTNU,XSTPNO,XPASNO,XRUNNO,XSTPSZ,XTRANS,XSAVE     ,XTMON,SKIP(
00105      9*         *4)
00106     10*          DIMENSION CTROLS(70)
00107     11*          COMMON /NAMES/E1,EOT1,C1,ROT1,RL,R1,RIT1,RLT1,JIT1,JOT1
00110     12*          COMMON /VOLTGS/VE1,VEOT1,VC1,VROT1,VRL,VR1,VRIT1,VRLT1,VJIT1,VJOT1
00111     13*          COMMON /CURNTS/IE1,IEOT1,IC1,IROT1,IRL,IR1,IRIT1,IRLT1,IJIT1,IJOT1
00112     14*          DIMENSION XR22D(  3),XC44D(  1),XR55D(  2),XE7(  2),XJ8(  2)
00113     15*          DIMENSION V2(  3),V4(  1),V5(  2),V7(  2),V8(  2)
00114     16*          DIMENSION I2(  3),I4(  1),I5(  2),I7(  2),I8(  2)
00115     17*          EQUIVALENCE (VR1,V2),(VC1,V4),(VROT1,V5),(VE1,V7),(VJIT1,V8)
00116     18*          EQUIVALENCE (IR1,I2),(IC1,I4),(IROT1,I5),(IE1,I7),(IJIT1,I8)
00117     19*          EQUIVALENCE (R1,XR22D),(C1,XC44D),(ROT1,XR55D),(E1,XE7),(JIT1,XJ8)
00120     20*          COMMON /SAVEIC/V4IC(  1)
00121     21*          COMMON /SAVICT/V4ICT(  1)
00122     22*          DIMENSION V4DOT(  1)
00123     23*          COMMON /DERIVS/DC1
00124     24*          COMMON /UTILTY/SAVETR(8,  1)
00125     25*          EQUIVALENCE (DC1,V4DOT)
00126     26*          DIMENSION PRAMTR(  1)
00127     27*          COMMON /PRMTRS/PJIT1
00130     28*          EQUIVALENCE (PRAMTR,PJIT1)
00131     29*          COMMON /OUTPTS/OTPOST(5,  4)
00132     30*          COMMON /OUTPUT/TPINDX(  5)
00133     31*          COMMON /OUTDTA/OUTBFR(  5)
00134     32*          EQUIVALENCE (CTROLS,TIME)
00135     33*          DATA NCL1C/  0/,NCL3C/  0/,NCL4C/  1/,NCL6C/  0/,NOPD/  0/
00135     34*    C     TRANSIENT INITIALIZATION
00143     35*          DIMENSION XMRGD(  3)
00144     36*          DIMENSION V2P(  3)
00145     37*          IF ( KSWIT.NE.0   ) GO TO 1
00147     38*          XMRGD(  1)=VJ1
00150     39*          XMRGD(  2)=RIT1
00151     40*          XMRGD(  3)=RLT1+ROT1+RL
00151     41*    C     TRANSIENT EQUATIONS
00152     42*        1 CONTINUE
00152     43*    C     V2P=-R25*R55D*(.35T*I3+R8ST*JR)-R24*V4-R27*E7
00153     44*          E1=EVOLT2(TIME)
00154     45*          V2P(  1)=-VC1-E1
00155     46*          V2P(  2)=-E1
00156     47*          VJIT1=-E1
00157     48*          EOT1=EQV741(TIME,VJIT1,IRIT1,PJIT1)
00160     49*          JOT1=EQJ741(TIME,VJIT1,IRIT1,PJIT1)
00161     50*          V2P(  3)=-ROT1*(+JOT1)+RL*(-JOT1)+EOT1
00162     51*          DO      10   N=     1   ,   3
00165     52*       10 I2(N)=V2P(N)/XMRGD(N)
00167     53*          DO      20   N=     1   ,   3
00172     54*       20 V2(N)=I2(N)*XR22D(N)
00172     55*    C     I5=.25T*I2+.35T*I3+R8ST*JR
00174     56*          IROT1=+IRLT1+JOT1
```

Figure 78. S I M T R Listing

```
00175    57*          IPL=-IPLT1-JOT1
00176    58*          DO       30   N=      1    ,    2
00201    59*       30 VS(N)=IS(N)*XMS,ED(N)
00201    60*     C    I4=R14T*I1+.4241*I2+R34T*I3+R84I*J8
00203    61*          IC1=+IR1
00204    62*          DO       40   N=      1    ,    1
00207    63*       40 V4DOT(N)=I4(N)/XC44D(N)
00211    64*          RETURN
00212    65*          END
```

Figure 78b. S I M T R Listing (cont.)

```
00101     1*          SUBROUTINE SIMUL8(KWAY)
00103     2*          IMPLICIT REAL (A-J,L-M,O-Z), INTEGER (K,N)
00103     3*     C    SCRIPRE/110R CIRCUIT ANALYSIS PROGRAM
00104     4*          COMMON /TAPES/NOUTTP,NTAPE,NLIBTP,NOUTP,NEDITP,NSAVTP
00105     5*          COMMON /CNTRLS/TIME,XSTOPT,XMXERT,XIR,XTISSS,XMNISS,XMXISS,XMNAIE,
00105     6*         *XMXAIE,XIC,XRERNO,XMXPAS,XMNRIE,XMAXIE,XMNISO,XMAICP,XICRER,XICAER
00105     7*         *,XMXOTP,XXDTMS,XYDTMS,XICPAS,XNOPRO,XNTNDX,XNHEAD,XNDFEQ,XERT,XNRE
00105     8*         *RN,XCNTOU,XSTPNO,XPASNO,XRUNNO,XSTPSZ,XTRANS,XSAVE     ,XTMON,SKIP(
00105     9*         *4)
00106    10*          DIMENSION CTROLS(70)
00107    11*          COMMON /NAMES/E1,EOT1,C1,ROT1,PL,R1,RIT1,RLT1,JIT1,JOT1
00110    12*          COMMON /VOLTGS/VE1,VEOT1,VC1,VROT1,VPL,VR1,VPIT1,VRLT1,VJIT1,VJOT1
00111    13*          COMMON /CURNTS/IE1,IEOT1,IC1,IROT1,IPL,IR1,IRIT1,IRLT1,IJIT1,IJOT1
00112    14*          DIMENSION XR22D(  3),XC44D(  1),XR55D(  2),XE7(  2),XJ8(  2)
00113    15*          DIMENSION V2(  3),V4(  1),V5(  2),V7(  2),V8(  2)
00114    16*          DIMENSION I2(  3),I4(  1),I5(  2),I7(  2),I8(  2)
00115    17*          EQUIVALENCE (VP1,V2),(VC1,V4),(VROT1,V5),(VE1,V7),(VJIT1,V8)
00116    18*          EQUIVALENCE (IP1,I2),(IC1,I4),(IROT1,I5),(IE1,I7),(IJIT1,I8)
00117    19*          EQUIVALENCE (R1,XR22D),(C1,XC44D),(ROT1,XR55D),(E1,XE7),(JIT1,XJ8)
00120    20*          COMMON /SAVEIC/V4IC(  1)
00121    21*          COMMON /SAVICT/V4ICT(  1)
00122    22*          DIMENSION V4DOT(  1)
00123    23*          COMMON /DERIVS/DC1
00124    24*          COMMON /UTILITY/SAVETB(8,  1)
00125    25*          EQUIVALENCE (DC1,V4DOT)
00126    26*          DIMENSION PRAMTR(  1)
00127    27*          COMMON /PRMTRS/PJIT1
00130    28*          EQUIVALENCE (PRAMTR,PJIT1)
00131    29*          COMMON /OUTPTS/OTPOST(5,  4)
00132    30*          COMMON /OUTPUT/TPINDX(  5)
00133    31*          COMMON /OUTDTA/OUTREF(  5)
00134    32*          EQUIVALENCE (CTROLS,TIME)
00135    33*          DATA NCL1C/  0/,NCL3C/  0/,NCL4C/  1/,NCL6C/  0/,NDPD/  0/
00135    34*     C    READ IN INPUT DATA
00143    35*          READ (NSAVTP,7000)XE7,XC44D,XR55D,XR22D,XJ8
00171    36*          READ (NSAVTP,7000)V7,V4,V5,V2,V8
00217    37*          READ (NSAVTP,7000)I7,I4,I5,I2,I8
00245    38*          READ (NSAVTP,7000)V4ICT
```

Figure 79a. S I M U L 8 Listing

```
00253    39*          READ (NSAVTP,7000)V4DOT
00261    40*          READ (NSAVTP,7000)PRAMTR
00267    41*          READ (NSAVTP,7400)OTRQST
00275    42*          READ (NSAVTP,7400)TPINDX
00303    43*          READ (NSAVTP,7400)ENDCRD
00306    44*     7000 FORMAT (5E14.7)
00307    45*     7100 FORMAT(12A6)
00310    46*     7200 FORMAT(1H0/(1X,1P8E14.7))
00311    47*     7400 FORMAT (12A6)
00312    48*     7500 FORMAT(1H0/(1X,12A6))
00313    49*     7600 FORMAT (1H0/(1X,12A6))
00314    50*          CALL TPHEAD
00314    51*    C     LOAD APPROPRIATE INITIAL CONDITIONS DATA
00315    52*          CALL XLOAD(V1IC,V1ICT,V1,NCL1C,I3IC,I3ICT,I3,NCL3C,V4IC,V4ICT,V4,N
00315    53*         *CL4C,I6IC,I6ICT,I6,NCL6C,   0,NWAY)
00315    54*    C     TRANSIENT INITIALIZATION
00316    55*          CALL SIMTR(KWAY,0)
00317    56*     9000 XPASNO=XPASNO+1.
00320    57*          CALL SIMTR(KWAY,1)
00321 *DIAGNOSTIC*  THE TEST FOR EQUALITY BETWEEN NON-INTEGERS MAY NOT BE MEANINGFUL.
00321    58*          IF (XSTPNO.EQ.0.) GO TO 9050
00323    59*     9010 CALL INTGRR(NOGO,I3,NCL3C,V4,NCL4C,PRAMTR, NDPD)
00324    60*          IF (NOGO.EQ.0) GO TO 9000
00324    61*    C     LOAD OUTPUT REQUESTS
00326    62*     9050 OUTBFR (  1)=TIME
00327    63*          OUTBFR (  2)=E1
00330    64*          IE1=-IR1-IRIT1-JIT1
00331    65*          OUTBFR (  3)=IE1
00332    66*          OUTBFR (  4)=VRL
00333    67*          OUTBFR (  5)=IRL
00334    68*          CALL OUTP(KWAY)
00335    69*          IF (KWAY.EQ.0) GO TO 9010
00335    70*    C     WRITE OUT THE COMPUTED VALUES
00337    71*     9090 REWIND NEDITP
00340    72*          WRITE (NEDITP,7001)CTRULS
00346    73*          WRITE (NEDITP,7001)XE7,XC44D,XR55D,XR22D,XJ8
00374    74*          WRITE (NEDITP,7001)V7,V4,V5,V2,V8
00422    75*          WRITE (NEDITP,7001)I7,I4,I5,I2,I8
00450    76*          WRITE (NEDITP,7001)V4IC
00456    77*          WRITE (NEDITP,7001)V4DOT
00464    78*          WRITE (NEDITP,7001)PRAMTR
00472    79*          WRITE (NEDITP,7400)OTRQST
00500    80*          WRITE (NEDITP,7400)TPINDX
00506    81*          WRITE (NEDITP,7400)ENDCRD
00511    82*     7001 FORMAT(1P5E14.7,10X)
00511    83*    C     LOAD APPROPRIATE TRANSIENT DATA
00512    84*          CALL XLOAD(V1IC,V1ICT,V1,NCL1C,I3IC,I3ICT,I3,NCL3C,V4IC,V4ICT,V4,N
00512    85*         *CL4C,I6IC,I6ICT,I6,NCL6C,   2,NWAY)
00512    86*    C     CHECK FOR PROGRAM SAVE
00513    87*          IF (KWAY.NE.9) GO TO 9100
00515    88*          CALL SAVEPD(1)
00516    89*          KWAY=0
00517    90*          GO TO 9010
00520    91*     9100 RETURN
00521    92*          END

          END OF UCC 1108 FORTRAN V COMPILATION.      1 *DIAGNOSTIC* MESSAGE(S)

PHASE  1 TIME    00:00.276
PHASE  2 TIME    00:00.019
```

Figure 79b. S I M U L 8 Listing (cont.)

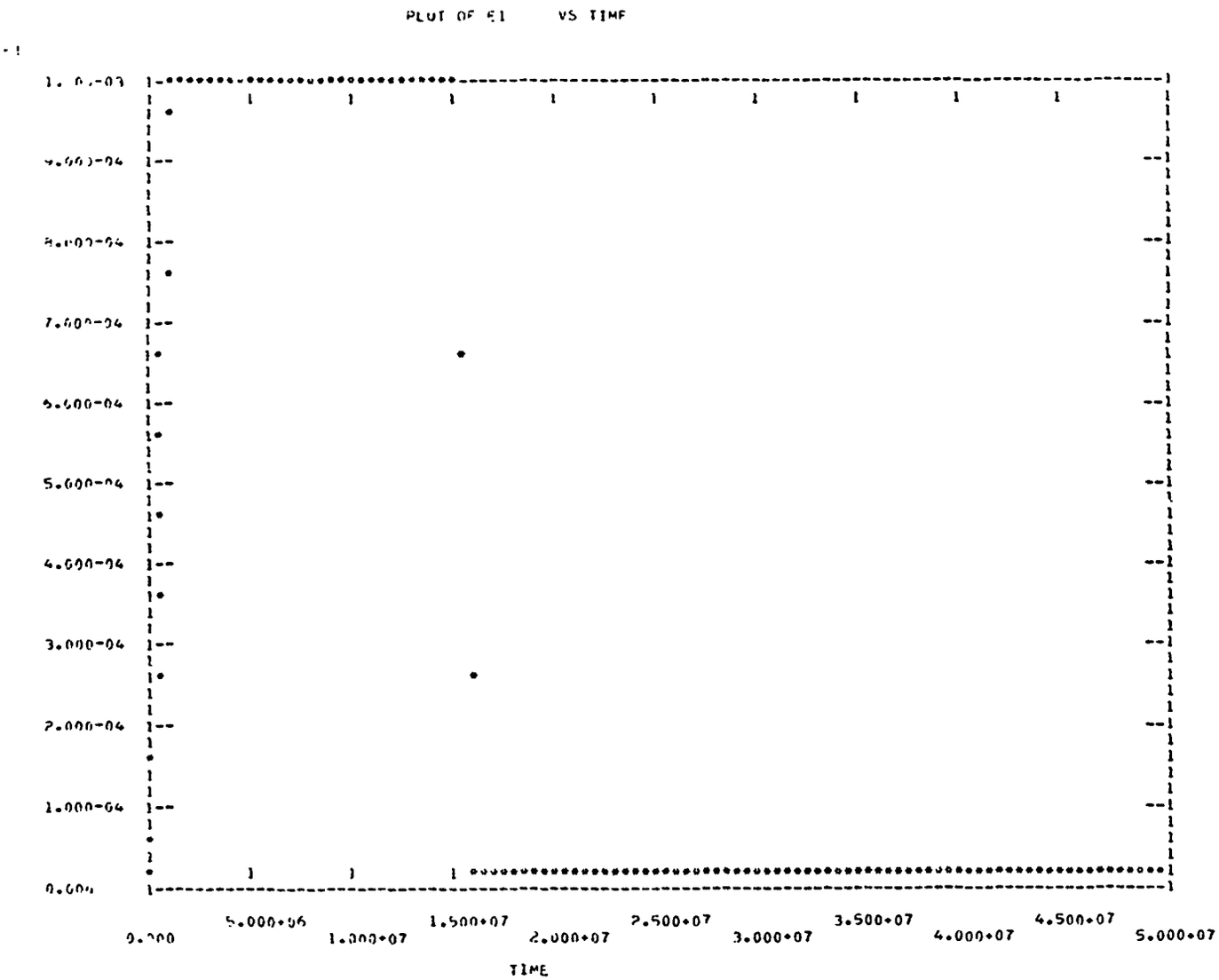


Figure 80a. SCEPTRE Plot of Input Voltage versus Time.

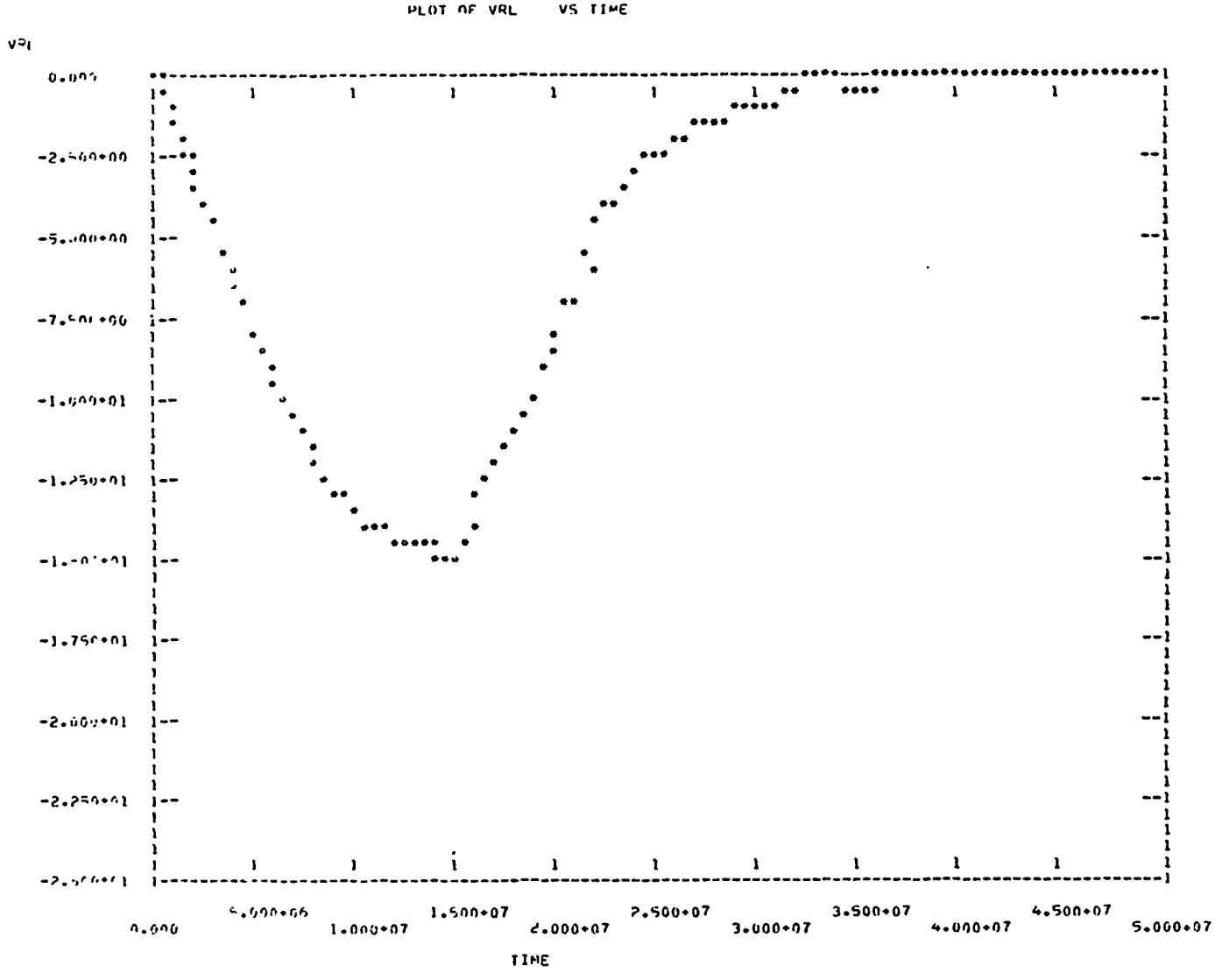


Figure 80b. SCEPTRE Plot of Output Voltage versus Time.

```
****    SAP2    ****    SAP2    ****    SAP2    ****    SAP2    ****    SAP2    ****

  ISURF( 1) = 0   ISURF( 2) = 0   ISURF( 3) = 1   ISURF( 4) = 0   ISURF( 5) = 0   ISURF( 6) = 0   ISURF( 7) = 0   ISURF( 8) = 0
 ISURF( 9) = 0   ISURF(10) = 0   ISURF(11) = 0   ISURF(12) = 0   ISURF(

FOR SURFACE  3, XLO =   .0000  , XHI =   50.00  , YLO =   .0000  , YHI =   2.400  , XDELTA =   2.632  , YDELTA =   .1263
 IXDIM = 20, IYDIM = 20, L = 3, ISYM = T       SCALE(3,1) =   .10-05  SCALE(3,2) =   .10-04  SCALE(3,3) =   .10-04

  IPONTR( 3, 1) =   1,    IPONTR( 3, 2) =   1,    IPONTR( 3, 3) =   1,

       IXBASE = 20    IYBASE = 20    IZBASE = 1200

INPUT THE VALUE OF JMAX, USE FORMAT I3,

THE VALUE OF JMAX AS READ IN IS   2

INPUT THE VALUES IN SEQUENCE OF J, CONFIG,NIN,NOUT,N,C, L, 4I3,3F12.4

 1 14  1  2      -.0000      -.0000      -.0000
 2  2  2  1      1.2920      -.0000      -.0000

THE MAXIMUM NUMBER OF INPUT NODES, NMAX=  2

 NODE   JPARAL   LMAX   LBLOCK

   1       0       1

                           LBLOCK( 1, 1)= 1

   2       0       1

                           LBLOCK( 2, 1)= 2

INPUT THE VALUE OF IWALL AND MMOD, 2I3,

IWALL = 1,   MMOD = 10

THE ITERATION CRITERIA,EPSLON =  .49999999-03

RADIATION TYPE =       NO RAD     DISTRIBUTION =
    THE 3 RESPECTIVE PARAMETERS ARE     -.00000       -.00000       -.00000
RADIATION TYPE =       NO RAD     DISTRIBUTION =
    THE 3 RESPECTIVE PARAMETERS ARE     -.00000       -.00000       -.00000

     IWALF( 1) =*****


TIME STEP OF TOO SMALL, WILL OVERFLOW U ARRAYS.
```

Figure 81a. SAP Printout during SCEPTRE run.

J	VIN(J)	CIN(J)	VOUT(J,1)	COUT(J,1)	VDIFF	CDIFF	VOUT(J,2)	COUT(J,2)	VOUT(J,3)	COUT(J,3)
1	-.190-04	.100-11	.142-02	.915-03	-.143-02	-.915-03	.000	.000	.000	.000

IWARGE(1) =****

TIME STEP DT TOO SMALL. WILL OVERFLOW U ARRAYS.

J	VIN(J)	CIN(J)	VOUT(J,1)	COUT(J,1)	VDIFF	CDIFF	VOUT(J,2)	COUT(J,2)	VOUT(J,3)	COUT(J,3)
1	-.190-04	-.200-07	.144-02	.725-03	-.145-02	-.725-03	.000	.000	.000	.000

J	VIN(J)	CIN(J)	VOUT(J,1)	COUT(J,1)	VDIFF	CDIFF	VOUT(J,2)	COUT(J,2)	VOUT(J,3)	COUT(J,3)
1	-.224-04	-.200-07	.342-02	.216-02	-.384-02	-.216-02	.000	.000	.000	.000

J	VIN(J)	CIN(J)	VOUT(J,1)	COUT(J,1)	VDIFF	CDIFF	VOUT(J,2)	COUT(J,2)	VOUT(J,3)	COUT(J,3)
1	-.595-04	-.447-07	.142-01	.799-02	-.143-01	-.799-02	.000	.000	.000	.000

J	VIN(J)	CIN(J)	VOUT(J,1)	COUT(J,1)	VDIFF	CDIFF	VOUT(J,2)	COUT(J,2)	VOUT(J,3)	COUT(J,3)
1	-.242-04	-.119-06	.236-01	.121-01	-.231-01	-.121-01	.000	.000	.000	.000

J	VIN(J)	CIN(J)	VOUT(J,1)	COUT(J,1)	VDIFF	CDIFF	VOUT(J,2)	COUT(J,2)	VOUT(J,3)	COUT(J,3)
1	-.159-03	-.164-06	.625-01	.328-01	-.626-01	-.328-01	.000	.000	.000	.000

J	VIN(J)	CIN(J)	VOUT(J,1)	COUT(J,1)	VDIFF	CDIFF	VOUT(J,2)	COUT(J,2)	VOUT(J,3)	COUT(J,3)
1	-.143-03	-.317-06	.780-01	.397-01	-.782-01	-.397-01	.000	.000	.000	.000

J	VIN(J)	CIN(J)	VOUT(J,1)	COUT(J,1)	VDIFF	CDIFF	VOUT(J,2)	COUT(J,2)	VOUT(J,3)	COUT(J,3)
1	-.257-03	-.366-06	.134	.689-01	-.135	-.689-01	.000	.000	.000	.000

J	VIN(J)	CIN(J)	VOUT(J,1)	COUT(J,1)	VDIFF	CDIFF	VOUT(J,2)	COUT(J,2)	VOUT(J,3)	COUT(J,3)
1	-.2-2-03	-.515-06	.154	.777-01	-.154	-.777-01	.000	.000	.000	.000

J	VIN(J)	CIN(J)	VOUT(J,1)	COUT(J,1)	VDIFF	CDIFF	VOUT(J,2)	COUT(J,2)	VOUT(J,3)	COUT(J,3)
1	-.356-03	-.564-06	.219	.111	-.219	-.111	.000	.000	.000	.000

M = 10. MPRINC = 10 ILOW = 1 IHIGH = 9 LSURF = 3

L	TIME2	VIN	DIL	TEMP	SUM	TSURF
2	.353+06	-.224-04	.125+05	-.530-03	.000	.190-02
3	.325+06	-.545-04	.375+05	-.422-02	-.530-03	.189-02
4	.300+06	-.942-04	.250+05	-.397-02	-.475-02	.189-02
5	.225+06	-.154-03	.750+05	-.223-01	-.872-02	.187-02
6	.200+06	-.141-03	.250+05	-.854-02	-.310-01	.186-02
7	.125+06	-.257-03	.750+05	-.356-01	-.395-01	.184-02
8	.100+06	-.232-03	.250+05	-.130-01	-.751-01	.184-02
9	.250+05	-.355-03	.750+05	-.491-01	-.881-01	.184-02

Figure 81b. SAP Printout during SCEPTRE run (cont.)

J	VIN(J)	CIN(J)	VOUT(J,1)	COUT(J,1)	VDIFF	CDIFF	VOUT(J,2)	COUT(J,2)	VOUT(J,3)	COUT(J,3)
1	-.331-03	-.713-06	.242	.122	-.242	-.122	.000	.000	.000	.000

J	VIN(J)	CIN(J)	VOUT(J,1)	COUT(J,1)	VDIFF	CDIFF	VOUT(J,2)	COUT(J,2)	VOUT(J,3)	COUT(J,3)
1	-.635-03	-.762-06	.322	.163	-.322	-.163	.000	.000	.000	.000

J	VIN(J)	CIN(J)	VOUT(J,1)	COUT(J,1)	VDIFF	CDIFF	VOUT(J,2)	COUT(J,2)	VOUT(J,3)	COUT(J,3)
1	-.688-03	-.911-06	.352	.177	-.352	-.177	.000	.000	.000	.000

J	VIN(J)	CIN(J)	VOUT(J,1)	COUT(J,1)	VDIFF	CDIFF	VOUT(J,2)	COUT(J,2)	VOUT(J,3)	COUT(J,3)
1	-.554-03	-.956-06	.457	.231	-.458	-.231	.000	.000	.000	.000

J	VIN(J)	CIN(J)	VOUT(J,1)	COUT(J,1)	VDIFF	CDIFF	VOUT(J,2)	COUT(J,2)	VOUT(J,3)	COUT(J,3)
1	-.579-03	-.111-05	.497	.250	-.497	-.250	.000	.000	.000	.000

J	VIN(J)	CIN(J)	VOUT(J,1)	COUT(J,1)	VDIFF	CDIFF	VOUT(J,2)	COUT(J,2)	VOUT(J,3)	COUT(J,3)
1	-.653-03	-.116-05	.627	.316	-.627	-.316	.000	.000	.000	.000

J	VIN(J)	CIN(J)	VOUT(J,1)	COUT(J,1)	VDIFF	CDIFF	VOUT(J,2)	COUT(J,2)	VOUT(J,3)	COUT(J,3)
1	-.673-03	-.131-05	.672	.338	-.672	-.338	.000	.000	.000	.000

J	VIN(J)	CIN(J)	VOUT(J,1)	COUT(J,1)	VDIFF	CDIFF	VOUT(J,2)	COUT(J,2)	VOUT(J,3)	COUT(J,3)
1	-.752-03	-.135-05	.803	.405	-.804	-.405	.000	.000	.000	.000

J	VIN(J)	CIN(J)	VOUT(J,1)	COUT(J,1)	VDIFF	CDIFF	VOUT(J,2)	COUT(J,2)	VOUT(J,3)	COUT(J,3)
1	-.892-03	-.156-05	.881	.443	-.881	-.443	.000	.000	.000	.000

J	VIN(J)	CIN(J)	VOUT(J,1)	COUT(J,1)	VDIFF	CDIFF	VOUT(J,2)	COUT(J,2)	VOUT(J,3)	COUT(J,3)
1	-.959-03	-.168-05	1.17	.591	-1.17	-.591	.000	.000	.000	.000

N = 20. NPOINT = 20 ILOW = 1 IHIGH = 19 ISURF = 3

L	TIME	DIN	DIL	TEMP	SUM	TSURF
2	.900+06	-.224-04	.125+05	-.532-03	.000	.190-07
3	.950+06	-.545-04	.375+05	-.423-02	-.532-03	.190-07
4	.925+06	-.942-04	.250+05	-.309-02	-.476-02	.189-07
5	.950+06	-.154-03	.750+05	-.222-01	-.875-02	.187-07
6	.925+06	-.183-03	.250+05	-.854-02	-.310-01	.186-07
7	.950+06	-.257-03	.750+05	-.356-01	-.395-01	.184-07
8	.925+06	-.298-03	.250+05	-.130-01	-.752-01	.184-07
9	.950+06	-.356-03	.750+05	-.491-01	-.881-01	.184-07
10	.925+06	-.391-03	.250+05	-.175-01	-.137	.184-07
11	.950+06	-.459-03	.750+05	-.631-01	-.155	.185-07
12	.925+06	-.493-03	.250+05	-.272-01	-.218	.185-07
13	.950+06	-.556-03	.750+05	-.745-01	-.240	.184-07
14	.925+06	-.592-03	.250+05	-.266-01	-.317	.184-07
15	.950+06	-.659-03	.750+05	-.891-01	-.343	.182-07
16	.925+06	-.692-03	.250+05	-.307-01	-.432	.181-07
17	.950+06	-.759-03	.750+05	-.101	-.463	.180-07
18	.900+06	-.892-03	.500+05	-.722-01	-.564	.180-07

Figure 81c. SAP Printout during SCEPTRE run (cont).

```
 19    .500+05   -.950-03    .150+00   -.262       -.637        .184-02

J    VIN(J)      CIN(J)     VOUT(J,1)   COUT(J,1)     VDIFF      CDIFF     VOUT(J,2)   COUT(J,2)   VOUT(J,3)   COUT(J,3)
1    -.100-02    -.191-05     1.30        .656       -1.31       -.656       .000        .000        .000        .000

J    VIN(J)      CIN(J)     VOUT(J,1)   COUT(J,1)     VDIFF      CDIFF     VOUT(J,2)   COUT(J,2)   VOUT(J,3)   COUT(J,3)
1    -.100-02    -.200-05     1.57        .788       -1.57       -.788       .000        .000        .000        .000

J    VIN(J)      CIN(J)     VOUT(J,1)   COUT(J,1)     VDIFF      CDIFF     VOUT(J,2)   COUT(J,2)   VOUT(J,3)   COUT(J,3)
1    -.100-02    -.200-05     1.66        .832       -1.66       -.832       .000        .000        .000        .000

J    VIN(J)      CIN(J)     VOUT(J,1)   COUT(J,1)     VDIFF      CDIFF     VOUT(J,2)   COUT(J,2)   VOUT(J,3)   COUT(J,3)
1    -.100-02    -.200-05     1.92        .965       -1.92       -.965       .000        .000        .000        .000

J    VIN(J)      CIN(J)     VOUT(J,1)   COUT(J,1)     VDIFF      CDIFF     VOUT(J,2)   COUT(J,2)   VOUT(J,3)   COUT(J,3)
1    -.100-02    -.200-05     2.02        1.01       -2.02       -1.01       .000        .000        .000        .000

J    VIN(J)      CIN(J)     VOUT(J,1)   COUT(J,1)     VDIFF      CDIFF     VOUT(J,2)   COUT(J,2)   VOUT(J,3)   COUT(J,3)
1    -.100-02    -.200-05     2.27        1.14       -2.28       -1.14       .000        .000        .000        .000

J    VIN(J)      CIN(J)     VOUT(J,1)   COUT(J,1)     VDIFF      CDIFF     VOUT(J,2)   COUT(J,2)   VOUT(J,3)   COUT(J,3)
1    -.100-02    -.200-05     2.37        1.19       -2.37       -1.19       .000        .000        .000        .000

J    VIN(J)      CIN(J)     VOUT(J,1)   COUT(J,1)     VDIFF      CDIFF     VOUT(J,2)   COUT(J,2)   VOUT(J,3)   COUT(J,3)
1    -.100-02    -.200-05     2.63        1.32       -2.63       -1.32       .000        .000        .000        .000

J    VIN(J)      CIN(J)     VOUT(J,1)   COUT(J,1)     VDIFF      CDIFF     VOUT(J,2)   COUT(J,2)   VOUT(J,3)   COUT(J,3)
1    -.100-02    -.200-05     2.72        1.36       -2.72       -1.36       .000        .000        .000        .000

J    VIN(J)      CIN(J)     VOUT(J,1)   COUT(J,1)     VDIFF      CDIFF     VOUT(J,2)   COUT(J,2)   VOUT(J,3)   COUT(J,3)
1    -.100-02    -.200-05     2.98        1.49       -2.98       -1.49       .000        .000        .000        .000

N = 30,  NPOINT = 30  ILOW =  1  IHIGH = 29  LSURF = 3

 L     TIME        DIF          DT          TEMP        SUM         TSURF
 2    .199+07   -.224-04    .125+05     -.534-03     .000        .192-02
 3    .195+07   -.595-04    .375+05     -.427-02    -.534-03     .191-02
 4    .193+07   -.942-04    .250+05     -.402-02    -.481-02     .191-02
 5    .185+07   -.159-03    .750+05     -.234-01    -.883-02     .188-02
 6    .182+07   -.147-03    .250+05     -.859-02    -.312-01     .188-02
 7    .175+07   -.257-03    .750+05     -.358-01    -.394-01     .185-02
 8    .172+07   -.242-03    .250+05     -.130-01    -.756-01     .185-02
 9    .165+07   -.396-03    .750+05     -.493-01    -.887-01     .184-02
10    .163+07   -.381-03    .250+05     -.176-01    -.138        .185-02
11    .155+07   -.459-03    .750+05     -.633-01    -.156        .185-02
12    .153+07   -.480-03    .250+05     -.223-01    -.219        .185-02
13    .145+07   -.554-03    .750+05     -.767-01    -.241        .184-02
14    .142+07   -.574-03    .250+05     -.266-01    -.318        .184-02
15    .135+07   -.653-03    .750+05     -.889-01    -.345        .181-02
16    .133+07   -.674-03    .250+05     -.306-01    -.433        .181-02
```

Figure 81d. SAP Printout during SCEPTRE Run (cont).

17	.125+07	-.7[illegible]-01	.750+05	-.101	-.484	.188-02
18	.129+07	-.[illegible]-01	.500+05	-.722-01	-.556	.188-02
19	.133+07	-.[illegible]-01	.150+06	-.260	-.638	.183-02
20	.136+07	-.168-02	.500+05	-.916-01	-.894	.183-02
21	.150+06	-.168-02	.150+06	-.276	-.990	.184-02
22	.300+06	-.[illegible]-02	.500+05	-.920-01	-1.27	.184-02
23	.350+06	-.168-02	.150+06	-.277	-1.36	.185-02
24	.500+06	-.168-02	.500+05	-.924-01	-1.63	.185-02
25	.450+06	-.168-02	.150+06	-.278	-1.73	.185-02
26	.[illegible]+06	-.168-02	.500+05	-.926-01	-2.00	.185-02
27	.[illegible]+06	-.168-02	.150+06	-.279	-2.10	.185-02
28	.[illegible]+06	-.168-02	.500+05	-.927-01	-2.37	.185-02
29	.500+06	-.168-02	.150+06	-.278	-2.47	.185-02

J	VIN(J)	CIN(J)	VOUT(J,1)	COUT(J,1)	VDIFF	CDIFF	VOUT(J,2)	COUT(J,2)	VOUT(J,3)	COUT(J,3)
1	-.168-02	-.200-05	3.07	1.54	-3.07	-1.54	.000	.000	.000	.000

J	VIN(J)	CIN(J)	VOUT(J,1)	COUT(J,1)	VDIFF	CDIFF	VOUT(J,2)	COUT(J,2)	VOUT(J,3)	COUT(J,3)
1	-.168-02	-.200-05	3.32	1.67	-3.32	-1.67	.000	.000	.000	.000

J	VIN(J)	CIN(J)	VOUT(J,1)	COUT(J,1)	VDIFF	CDIFF	VOUT(J,2)	COUT(J,2)	VOUT(J,3)	COUT(J,3)
1	-.168-02	-.200-05	3.50	1.76	-3.50	-1.76	.000	.000	.000	.000

J	VIN(J)	CIN(J)	VOUT(J,1)	COUT(J,1)	VDIFF	CDIFF	VOUT(J,2)	COUT(J,2)	VOUT(J,3)	COUT(J,3)
1	-.168-02	-.200-05	4.01	2.01	-4.01	-2.01	.000	.000	.000	.000

J	VIN(J)	CIN(J)	VOUT(J,1)	COUT(J,1)	VDIFF	CDIFF	VOUT(J,2)	COUT(J,2)	VOUT(J,3)	COUT(J,3)
1	-.168-02	-.200-05	4.19	2.10	-4.19	-2.10	.000	.000	.000	.000

J	VIN(J)	CIN(J)	VOUT(J,1)	COUT(J,1)	VDIFF	CDIFF	VOUT(J,2)	COUT(J,2)	VOUT(J,3)	COUT(J,3)
1	-.168-02	-.200-05	4.69	2.35	-4.69	-2.35	.000	.000	.000	.000

J	VIN(J)	CIN(J)	VOUT(J,1)	COUT(J,1)	VDIFF	CDIFF	VOUT(J,2)	COUT(J,2)	VOUT(J,3)	COUT(J,3)
1	-.168-02	-.200-05	4.86	2.44	-4.86	-2.44	.000	.000	.000	.000

J	VIN(J)	CIN(J)	VOUT(J,1)	COUT(J,1)	VDIFF	CDIFF	VOUT(J,2)	COUT(J,2)	VOUT(J,3)	COUT(J,3)
1	-.168-02	-.200-05	5.35	2.68	-5.35	-2.68	.000	.000	.000	.000

J	VIN(J)	CIN(J)	VOUT(J,1)	COUT(J,1)	VDIFF	CDIFF	VOUT(J,2)	COUT(J,2)	VOUT(J,3)	COUT(J,3)
1	-.168-02	-.200-05	5.52	2.77	-5.52	-2.77	.000	.000	.000	.000

J	VIN(J)	CIN(J)	VOUT(J,1)	COUT(J,1)	VDIFF	CDIFF	VOUT(J,2)	COUT(J,2)	VOUT(J,3)	COUT(J,3)
1	-.168-02	-.200-05	5.98	3.00	-5.98	-3.00	.000	.000	.000	.000

M = 40, MAXIMF = 40 ILOW = 1 IHIGH = 39 ISURF = 3

L	TIMEP	QIN	QTL	TEMP	SUM	TSURF
2	.354+07	-.224-04	.125+05	-.536-03	.000	.192-02
3	.360+07	-.595-04	.375+05	-.425-02	-.536-03	.191-02
4	.377+07	-.942-04	.250+05	-.400-02	-.479-02	.190-02

Figure 81e. SAP Printout during SCEPTRE Run (cont).

FORCING FUNCTION OPTION = 2

A PIECEWISE LINEAR FORCE FUNCTION IS USED WITH THE NUMBER OF STEPS = 5

FUNCTION	TIME	UNIT
.1000-04	.0000	MILLIS
.1000-02	1.000	MILLIS
.1000-02	15.00	MILLIS
.1000-04	16.00	MILLIS
.1000-04	50.00	MILLIS

5 MILLIS 50 MILLIS 0 MILLIS 101 LINEAR

LINEAR TIME STEPS ARE USED.

Figure 81f. SAP Printout during SCEPTRE Run (cont).

TRANSIENT SOLUTION CONTROLS AFTER SIMULATION

INTEGRATION ROUTINE	XPO
CURRENT SIMULATION TIME	5.0150000+07
INTEGRATION STEP COUNTER	1.3600000+02
INTEGRATION PASS COUNTER	2.7100000+02
SOLUTION EXECUTION TIME(ELAPSED)	1.2833333+00
TERMINATION CONDITION	STOP TIME EXCEEDED (NORMAL STOP)

Figure 82a. SCEPTRE Printout during SCEPTRE Run.

TRANSIENT ANALYSIS RESULTS

TIME	0.00000	5.00000E-04	1.50000E-03	2.50000E-03	3.50000E-03	4.50000E-03	5.50000E-03
E1	1.00000E-03	5.45000E-03	1.54500E-02	2.57500E-02	3.58500E-02	4.55500E-02	5.54500E-02
IE1	2.20000E-07	1.19900E-06	3.48700E-06	5.66500E-06	7.84300E-06	1.00210E-05	1.21990E-05
VBL	-1.44474E-03	-1.57797E-02	-6.56674E-02	-1.37401E-01	-2.22626E-01	-3.25985E-01	-4.62040E-01
IBL	-7.24269E-04	-7.38536E-03	-3.28337E-02	-6.89003E-02	-1.11313E-01	-1.62993E-01	-2.31040E-01

TIME	6.50000E-03	7.50000E-03	9.50000E-03	1.15000E-02	1.35000E-02	1.55000E-02	1.75000E-02
E1	6.53500E-02	7.52500E-02	9.50500E-02	1.00000E-01	1.00000E-01	1.00000E-01	1.00000E-01
IE1	1.43770E-05	1.65510E-05	2.04110E-05	2.20000E-05	2.20000E-05	2.20000E-05	2.19999E-05
VBL	-6.12100E-01	-8.09494E-01	-1.18179E+00	-1.57483E+00	-1.92432E+00	-2.28313E+00	-2.63562E+00
IBL	-3.16650E-01	-4.18744E-01	-6.90895E-01	-7.87416E-01	-9.64659E-01	-1.14157E+00	-1.31791E+00

TIME	1.95000E-02	2.15000E-02	2.55000E-02	2.95000E-02	3.35000E-02	3.75000E-02	4.15000E-02
E1	1.00000E-01	1.00000E-01	1.00000E-01	1.00000E-01	1.00000E-01	1.00000E-01	1.00000E-01
IE1	2.19999E-05	2.19999E-05	2.19999E-05	2.19999E-05	2.19999E-05	2.19999E-05	2.19999E-05
VBL	-2.98559E+00	-3.33513E+00	-4.02410E+00	-4.70421E+00	-5.36539E+00	-6.00381E+00	-6.61896E+00
IBL	-1.49368E+00	-1.66497E+00	-2.01305E+00	-2.35210E+00	-2.68269E+00	-3.00190E+00	-3.30948E+00

TIME	4.55000E-02	4.95000E-02	5.35000E-02	5.75000E-02	6.15000E-02	6.55000E-02	6.95000E-02
E1	1.00000E-01	1.00000E-01	1.00000E-01	1.00000E-01	1.00000E-01	1.00000E-01	1.00000E-01
IE1	2.19998E-05	2.19998E-05	2.19998E-05	2.19998E-05	2.19998E-05	2.19998E-05	2.19997E-05
VBL	-7.21379E+00	-7.79152E+00	-8.35147E+00	-8.92170E+00	-9.46230E+00	-1.00032E+01	-1.05401E+01
IBL	-3.60659E+00	-3.89561E+00	-4.17599E+00	-4.46085E+00	-4.73115E+00	-5.00159E+00	-5.27003E+00

TIME	7.35000E-02	7.75000E-02	8.15000E-02	8.55000E-02	8.95000E-02	9.35000E-02	9.75000E-02
E1	1.00000E-01	1.00000E-01	1.00000E-01	1.00000E-01	1.00000E-01	1.00000E-01	1.00000E-01
IE1	2.19997E-05	2.19997E-05	2.19997E-05	2.19997E-05	2.19997E-05	2.19996E-05	2.19996E-05
VBL	-1.10632E+01	-1.15526E+01	-1.20308E+01	-1.24579E+01	-1.29317E+01	-1.31590E+01	-1.34390E+01
IBL	-5.53139E+00	-5.78132E+00	-6.01537E+00	-6.22496E+00	-6.46584E+00	-6.57951E+00	-6.71952E+00

TIME	1.01500E-01	1.05500E-01	1.09500E-01	1.13500E-01	1.17500E-01	1.21500E-01	1.25500E-01
E1	1.00000E-01	1.00000E-01	1.00000E-01	1.00000E-01	1.00000E-01	1.00000E-01	1.00000E-01
IE1	2.19996E-05	2.19996E-05	2.19996E-05	2.19996E-05	2.19995E-05	2.19995E-05	2.19995E-05
VBL	-1.36744E+01	-1.38795E+01	-1.40675E+01	-1.41877E+01	-1.43076E+01	-1.44169E+01	-1.45149E+01
IBL	-6.83920E+00	-6.93973E+00	-7.02377E+00	-7.09385E+00	-7.15379E+00	-7.20847E+00	-7.25746E+00

TIME	1.29500E-01	1.33500E-01	1.37500E-01	1.41500E-01	1.45500E-01	1.49500E-01	1.53500E-01
E1	1.00000E-01	1.00000E-01	1.00000E-01	1.00000E-01	1.00000E-01	1.00000E-01	6.53500E-04
IE1	2.19995E-05	2.19995E-05	2.19995E-05	2.19994E-05	2.19994E-05	2.19994E-05	1.43764E-05
VBL	-1.45393E+01	-1.46683E+01	-1.47222E+01	-1.47591E+01	-1.47868E+01	-1.48182E+01	-1.44908E+01
IBL	-7.23995E+00	-7.33413E+00	-7.36110E+00	-7.37955E+00	-7.39442E+00	-7.40911E+00	-7.24042E+00

TIME	1.57500E-01	1.61500E-01	1.65500E-01	1.69500E-01	1.73500E-01	1.77500E-01	1.81500E-01
E1	2.57500E-04	1.00000E-05	1.00000E-05	1.00000E-05	1.00000E-05	1.00000E-05	1.00000E-05
IE1	5.66439E-06	2.19344E-07	2.19388E-07	2.19388E-07	2.19388E-07	2.19388E-07	2.19388E-07
VBL	-1.38985E+01	-1.32715E+01	-1.26606E+01	-1.21540E+01	-1.16877E+01	-1.12431E+01	-1.08013E+01
IBL	-6.94625E+00	-6.61074E+00	-6.33030E+00	-6.07702E+00	-5.84385E+00	-5.62155E+00	-5.40066E+00

Figure 82b. SCEPTRE Printout during SCEPTRE Run (cont).

TRANSIENT ANALYSIS RESULTS

TIME	1.89500+07	1.89500+07	1.93500+07	1.97500+07	2.01500+07	2.05500+07	2.09500+07
E1	1.00000-05	1.00000-05	1.00000-05	1.00000-05	1.00000-05	1.00000-05	1.00000-05
IE1	2.19384-07	2.19384-07	2.19384-07	2.19384-07	2.19384-07	2.19384-07	2.19384-07
VBL	-1.03341+01	-9.81492+00	-8.85298+00	-8.71402+00	-8.13992+00	-6.94417+00	-6.89701+00
IBL	-5.16705+00	-4.90711+00	-4.42649+00	-4.35701+00	-4.06996+00	-3.47208+00	-3.44851+00
TIME	2.13500+07	2.17500+07	2.21500+07	2.25500+07	2.29500+07	2.33500+07	2.37500+07
E1	1.00000-05	1.00000-05	1.00000-05	1.00000-05	1.00000-05	1.00000-05	1.00000-05
IE1	2.19384-07	2.19384-07	2.19384-07	2.19384-07	2.19384-07	2.19384-07	2.19385-07
VBL	-5.74[illegible]	-3.78356+00	-4.71986+00	-4.27931+00	-3.82128+00	-3.46252+00	-3.15083+00
IBL	-2.87449+00	-2.89284+00	-2.35930+00	-2.11965+00	-1.91064+00	-1.73126+00	-1.57541+00
TIME	2.41500+07	2.45500+07	2.49500+07	2.53500+07	2.57500+07	2.61500+07	2.65500+07
E1	1.00000-05	1.00000-05	1.00000-05	1.00000-05	1.00000-05	1.00000-05	1.00000-05
IE1	2.19385-07	2.19385-07	2.19385-07	2.19385-07	2.19385-07	2.19385-07	2.19384-07
VBL	-2.57973+00	-2.44427+00	-2.43966+00	-2.25105+00	-2.10276+00	-1.95503+00	-1.81625+00
IBL	-1.43996+00	-1.32213+00	-1.21983+00	-1.13052+00	-1.05138+00	-9.77515-01	-9.08123-01
TIME	2.69500+07	2.73500+07	2.77500+07	2.81500+07	2.85500+07	2.89500+07	2.93500+07
E1	1.00000-05	1.00000-05	1.00000-05	1.00000-05	1.00000-05	1.00000-05	1.00000-05
IE1	2.19384-07	2.19384-07	2.19384-07	2.19384-07	2.19384-07	2.19383-07	2.19383-07
VBL	-1.68805+00	-1.57215+00	-1.47029+00	-1.38414+00	-1.31399+00	-1.24584+00	-1.17876+00
IBL	-7.44027-01	-7.26077-01	-7.35134-01	-6.92071-01	-6.56993-01	-6.22919-01	-5.89378-01
TIME	2.97500+07	3.01500+07	3.05500+07	3.09500+07	3.13500+07	3.17500+07	3.21500+07
E1	1.00000-05	1.00000-05	1.00000-05	1.00000-05	1.00000-05	1.00000-05	1.00000-05
IE1	2.19383-07	2.19383-07	2.19383-07	2.19383-07	2.19382-07	2.19382-07	2.19382-07
VBL	-1.15664+00	-1.03243+00	-9.23209-01	-8.01090-01	-6.68746-01	-4.78300-01	-3.15607-01
IBL	-5.53341-01	-5.11744-01	-4.61403-01	-4.00545-01	-3.24373-01	-2.39150-01	-1.57603-01
TIME	3.25500+07	3.29500+07	3.33500+07	3.37500+07	3.41500+07	3.45500+07	3.49500+07
E1	1.00000-05	1.00000-05	1.00000-05	1.00000-05	1.00000-05	1.00000-05	1.00000-05
IE1	2.19382-07	2.19382-07	2.19382-07	2.19381-07	2.19381-07	2.19381-07	2.19381-07
VBL	-1.83691-01	-1.63554-01	-9.67307-02	-1.32233-01	-1.86073-01	-2.50967-01	-3.17079-01
IBL	-9.18454-02	-5.17462-02	-4.83654-02	-6.61164-02	-9.30367-02	-1.25494-01	-1.58540-01
TIME	3.53500+07	3.57500+07	3.61500+07	3.65500+07	3.69500+07	3.73500+07	3.77500+07
E1	1.00000-05	1.00000-05	1.00000-05	1.00000-05	1.00000-05	1.00000-05	1.00000-05
IE1	2.19381-07	2.19381-07	2.19380-07	2.19380-07	2.19380-07	2.19380-07	2.19380-07
VBL	-4.27795-01	-3.63927-01	-2.25447-01	-2.25715-01	-2.25716-01	-2.25716-01	-2.25716-01
IBL	-3.13595-01	-1.81514-01	-1.12744-01	-1.12858-01	-1.12858-01	-1.12858-01	-1.12858-01
TIME	3.81500+07	3.85500+07	3.89500+07	3.93500+07	3.97500+07	4.01500+07	4.05500+07
E1	1.00000-05	1.00000-05	1.00000-05	1.00000-05	1.00000-05	1.00000-05	1.00000-05
IE1	2.19380-07	2.19380-07	2.19379-07	2.19379-07	2.19379-07	2.19379-07	2.19379-07
VBL	-2.25716-01	-2.25716-01	-2.25716-01	-2.25716-01	-2.25716-01	-2.25716-01	-2.25716-01
IBL	-1.12858-01	-1.12858-01	-1.12858-01	-1.12858-01	-1.12858-01	-1.12858-01	-1.12858-01

Figure 82c. SCEPTRE Printout during SCEPTRE Run (cont).

TRANSIENT ANALYSIS RESULTS

TIME	4.09500+07	4.13500+07	4.17500+07	4.21500+07	4.25500+07	4.29500+07	4.33500+07
E1	1.00000-05	1.00000-05	1.00000-05	1.00000-05	1.00000-05	1.00000-05	1.00000-05
IE1	2.19377+07	2.19378+07	2.19378+07	2.19378+07	2.19378+07	2.19378+07	2.19378+07
VBL	-2.25716+01	-2.25716-01	-2.25716-01	-2.25716-01	-2.25716-01	-2.25716-01	-2.25716-01
IBL	-1.12854-01	-1.12858-01	-1.12858-01	-1.12858-01	-1.12858-01	-1.12858-01	-1.12858-01

TIME	4.37500+07	4.41500+07	4.45500+07	4.49500+07	4.53500+07	4.57500+07	4.61500+07
E1	1.00000-05	1.00000-05	1.00000-05	1.00000-05	1.00000-05	1.00000-05	1.00000-05
IE1	2.19377+07	2.19377-07	2.19377-07	2.19377-07	2.19377-07	2.19377-07	2.19376-07
VBL	-2.25716-01	-2.25716-01	-2.25716-01	-2.25716-01	-2.25716-01	-2.25716-01	-2.25716-01
IBL	-1.12854-01	-1.12854-01	-1.12858-01	-1.12858-01	-1.12858-01	-1.12858-01	-1.12858-01

TIME	4.65500+07	4.69500+07	4.73500+07	4.77500+07	4.81500+07	4.85500+07	4.89500+07
E1	1.00000-05	1.00000-05	1.00000-05	1.00000-05	1.00000-05	1.00000-05	1.00000-05
IE1	2.19376+07	2.19376+07	2.19376-07	2.19376-07	2.19376-07	2.19375-07	2.19375-07
VBL	-2.25716-01	-2.25716-01	-2.25716-01	-2.25716-01	-2.25716-01	-2.25716-01	-2.25716-01
IBL	-1.12854-01	-1.12858-01	-1.12858-01	-1.12858-01	-1.12858-01	-1.12858-01	-1.12858-01

TIME	4.93500+07	4.97500+07	5.01500+07
E1	1.00000-05	1.00000-05	-3.37485-02
IE1	2.19375+07	2.19375-07	-7.43568-04
VBL	-2.25716-01	-2.25716-01	4.14962+00
IBL	-1.12858-01	-1.12858-01	2.07481+00

Figure 82d. SCEPTRE Printout during SCEPTRE Run (cont).

zero throughout. Normally in a SAP execution the iteration cycle in MAIN is printed out during each time step, but the basic iteration strategy of SAP is out of action because SCEPTRE has the last output node. Hence iteration results are not printed in the listing of Figure 81 by SAP.

The printer plot output by SCEPTRE from the run is contained in Figure 80.

SECTION VIII

CONCLUSIONS

Emphasis has been given during this research program to finding out whether reasonable hope exists for treating radiation effects on electronic components using strictly numerical representations of time domain input-output response surfaces. It was seen that convolution works reasonably well for the class of non-linearity represented by a saturating op amp.

Probably a clear cut major advantage of the approach is the immediate grasp of the intricacies of the radiation response over the domains of the dose and time variables which the surface presentations provide. If suitable data acquisition systems and data reduction equipment are made on-line accessories at the major radiation facilities in the country, then surfaces such as presented here could be obtained while the data is being taken. If a picture is worth a thousand words, certainly a surface is worth several dozens of Polaroid pictures of single events. The surface representation is far more readily remembered.

The original surface representations for the 741 were rather laboriously drawn by hand using large three dimensional perspective grids. The one advantage of the technique was that human judgement was directly applied in resolving inconsistencies between data sets, smoothing and interpolating where needed. The first results thus looked good subjectively. The data sets for the 9704 gate were treated solely by computer processing methods. By judicious use of wild-pointing, smoothing, and interpolation routines, and by culling completely inconsistent data sets, surfaces could be obtained whose smoothness is again a matter of subjective choice. If appropriate data reduction equipment is available at the radiation site, the computer processing strategies are clearly the way to go.

The basic computational techniques involved in the Propagation of Bivariable Response Functions were tried for some relatively simple circuit configurations. A learning process was evident in treating the parallel block algorithm. If the transfer functions contain the output variables, then a self-consistency loop is required in the iteration process to produce a stable convergence. The precision of the solution was about 0.1 percent for the case of a feedback loop around an op amp. The gain calculated was precisely that expected. The response of the op amp to sine waves yielded expected values for the phase shift with frequency.

Care must be taken in very slow phenomena that the time steps are small enough that enough partitions are created to correctly sample the device dynamics. If the device is nonlinear, more time steps may be required in the nonlinear region than in the linear region.

The radiation response simulations have good computational characteristics so far as large scale computer processing is concerned. Runs were made that involved convolving or interpolating on four surfaces simultaneously, with execution times on the UNIVAC 1108 of six seconds per 50 time steps. All the surfaces treated here were fit with a 20 x 20 fitting grid, and thus required 1200 numbers to represent them. Some surfaces might be adequately fit with a smaller number. It was also pointed out that if the surface values are obtained by calculation based on a lower level system analysis rather than from experimental data, it is not necessary to least square justify the information. The computer time required to generate the three dimensional fit is then lowered drastically. Thus from the point of view of the important system analysis concept of staging of complexity levels, the machine execution time requirements are entirely reasonable.

Logarithmic time bases were seen to be advantageous in fitting certain classes of surfaces. If the device makes a rapid transition from a fast to a slow phenomena, then such a time base works well, both for the surface and the simulation. Problems can be encountered in using such a time base on a surface which is short relative to the time steps, as the time step changes during the computation. In this case a convolutional strategy will probably have to make a transition to a single partition look-up process.

The merging of the techniques of SAP with SCEPTRE seemed relatively straightforward. The amount of core space remaining available to the user hopefully might be increased when the matrix dimensions in SCEPTRE become adjustable. If a block technique is used, the nodal complexity should be reduced.

While it is conceivable that higher dimensionality surfaces than the three dimensional ones treated here might be required for general cases, no attention was directed to them in the work covered here. This is a question to be examined if the three dimensional surface concept does prove of value. Work is being done at LMSC in improving the computer aspects of dealing with surfaces of higher dimensionality.

The results obtained in this contract seem encouraging in terms of computational characteristics, and enlightening in terms of understanding and visualizing the effects of radiation on devices. Summarizing then:

Established Advantages or Conclusions

- Surfaces provide rich intuitive understanding of device electrical and radiation responses.
- On-line computer reduction of radiation effects data to the surface form seems practical.
- Engineering precision of output response prediction can be achieved by the bivariable response function propagation method.
- The computer execution time and storage required are entirely acceptable.
- A completely numerical representation of device dynamics can be used for circuit analysis.
- Staging of complexity levels in system analysis by computer calculation of response surfaces should have acceptable execution times for surface fitting.
- Logarithmic time bases and steps can be used for certain devices radiation simulation.
- SCEPTRE is adaptable to this method.

Areas of Suggested Further Study

- Best mix of iteration strategies in combination series and parallel circuits.
- Actual trial of staging of complexity levels in system analysis by this method.
- Transition between convolution and single partition surface look-up to calculate responses.
- Use of surfaces having dimensionality higher than three.
- Application to wider classes of devices and systems.
- Failure mechanism analysis of the permanent degradation observed on the 741s.

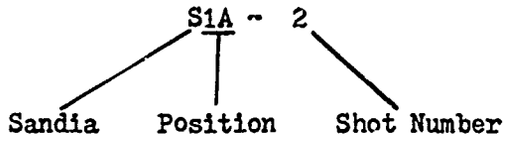
APPENDIX

TECHNIQUES USED FOR REACTOR TESTS OF DEVICES

The sample devices were held to styrofoam assemblies held at seven distances from the core centerline, as given in the Test Plan we had submitted earlier to White Sands. The overall situation in the reactor room is shown in Figure 83. The photograph shows five of the styrofoam blocks mounted to the pegboard table. Two other blocks are out of the field of view off to the left at distances of 7 and 12 feet from core centerline. Careful inspection of the drawing in the frame on the far wall of the cave shows a plan drawing of the reactor core itself. Note the "glory hole" down the core axis for maximum neutron dosages.

Since the different holders portray different angles relative to the lens axis, the way in which the devices are attached and positioned relative to the reactor core become evident. Affixed in the leftmost holder are two cables (laced with blue tape and orange tape) holding mother sockets containing one 9704 and one 741 respectively. (The 9704 is a flat-pak and doesn't stick out as far as the DIP 741 package.) The sockets are mounted on 3 x 4 in.-pieces of flat white plastic 1/16th inch thick. A black plastic ferrule, which can't be seen, fits around the cable on the back side of the plastic, and is potted with Silastic RTV to hold the wires to the socket better. The ferrule nests in a 1 in.-cut into the front face of the styrofoam block, as shown in Figure 84. Styrofoam is an easy material to work with, and has low density which is important from the point of view of minimizing interaction with the core fission characteristics.

The dosimetry employed during the shots consisted of sulfur in aluminum cans, which measures the integrated fast neutron flux, and TLD's or thermoluminescent detectors of LiF, which is responsive to the gamma flux. These were coded as follows:



The dosimeters were held in position on the styrofoam blocks by masking tape, so that rapid changes could be made between reactor bursts reducing exposure of personnel to the radiation from the walls of the reactor room.

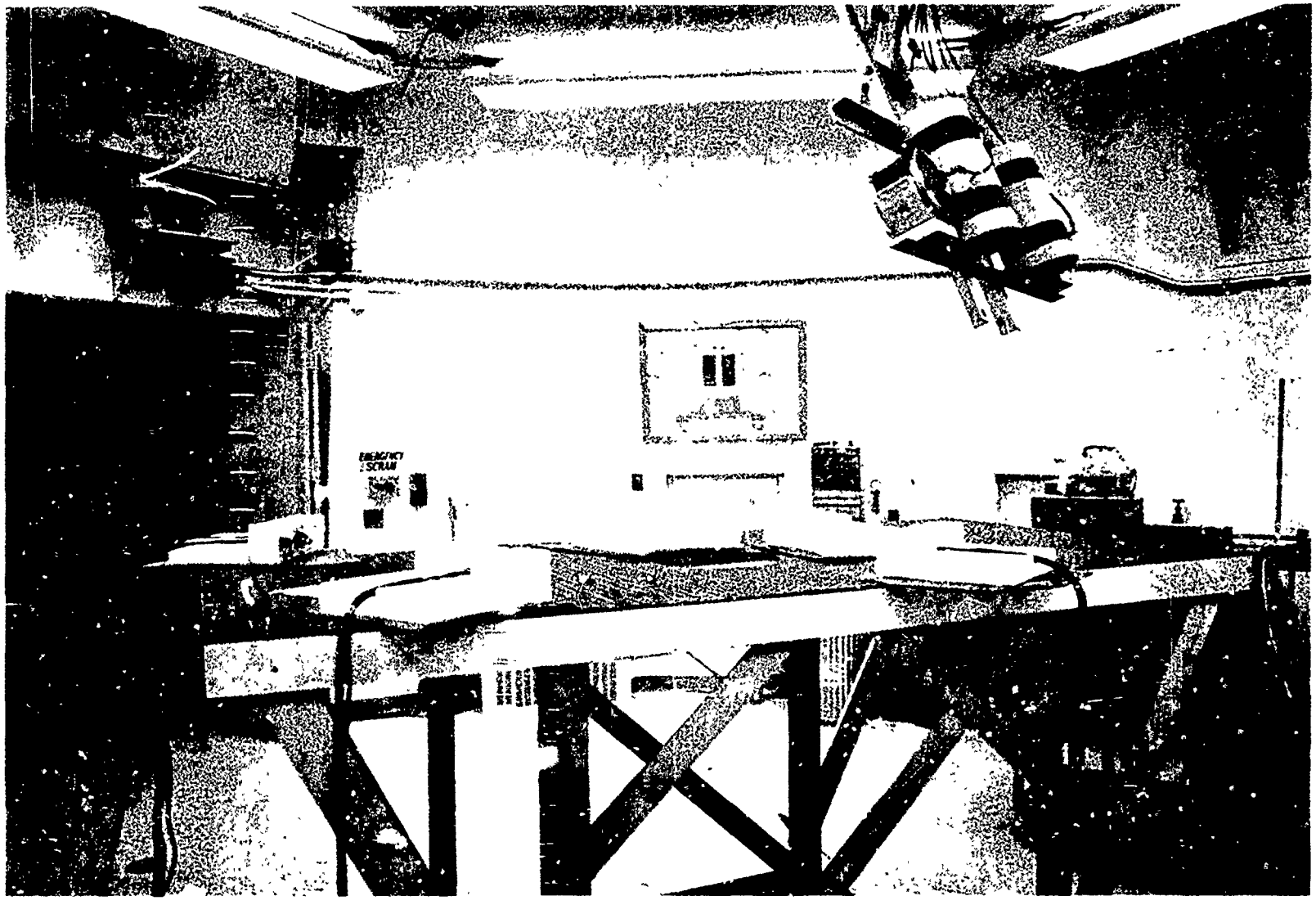


Figure 83. Sandia Pulse Reactor Room showing 4' x 8' Pegboard Table Attached to Aluminum Support Table, and with Styrofoam Blocks held to it and Holding Samples in Sockets. Note Dress of Cables.

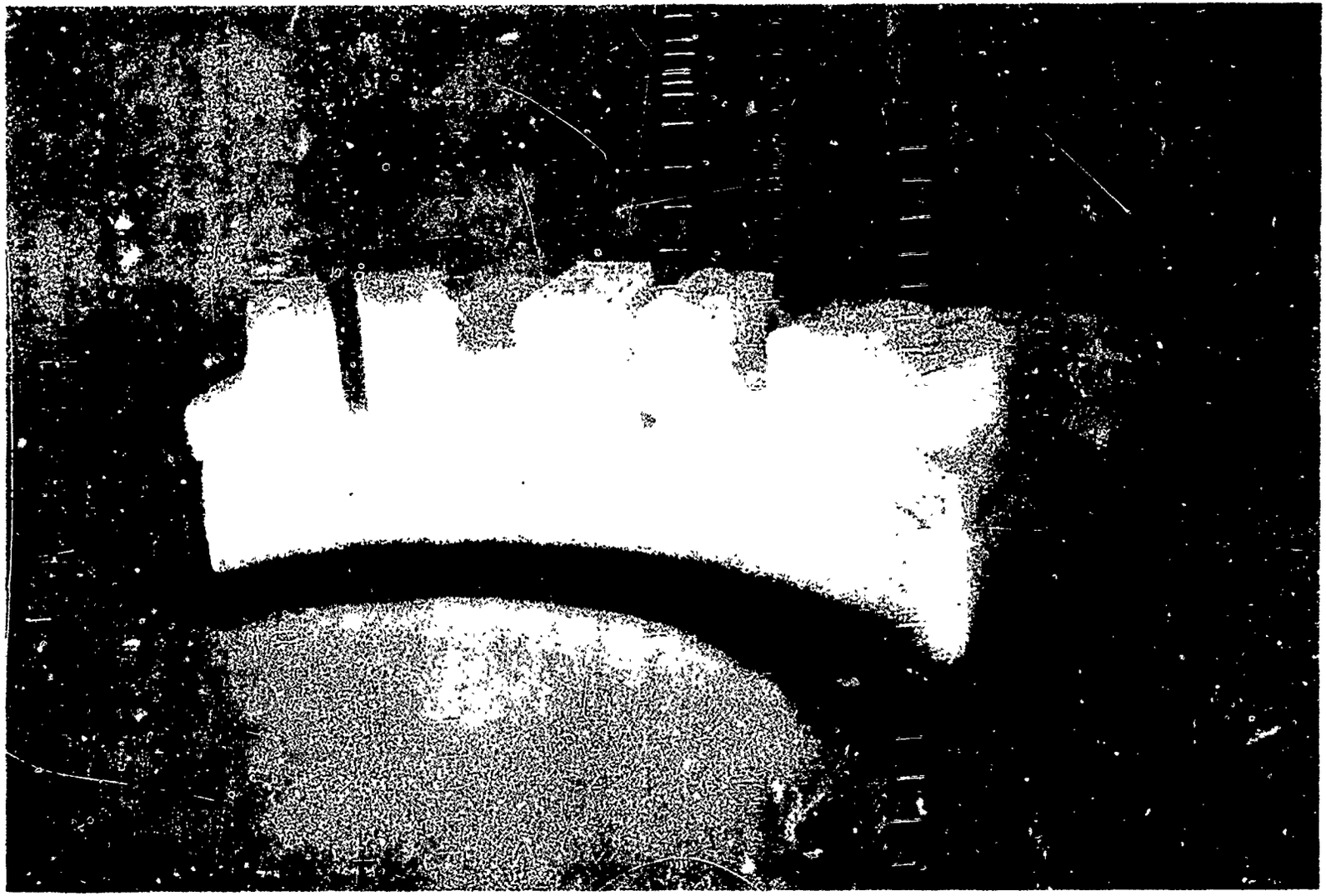
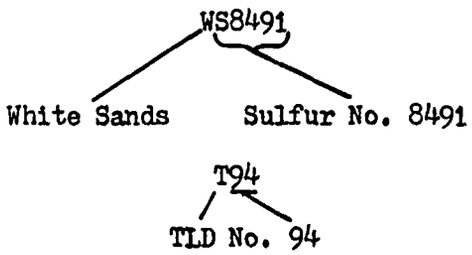


Figure 84. Typical Styrofoam Block to Hold Devices. Radius of Inside Surface provides Equidistant Exposures for up to Three Devices. The Ferrule on the Back of a Socket Plate fits into a One Inch Hole in the Block. Cable Slips in Groove.

For the White Sands dosimeters mounted for cross-calibration puposes



These dosimeters were affixed to the face of the styrofoam blocks with masking tape. The devices project 1" closer to the core than the dosimeters from the face of the block, and the final dosage computations were corrected for this difference assuming inverse square intensity change with distance. No attempt was made to alter the fission n - γ ratio by lead shielding. If lead is placed close to the reactor core, significant perturbations in the reactor pulse result.

Safety block and control rod adjustment controls are the means by which the desired burst pulse is achieved. This is most conveniently discussed in terms of the temperature rise of the core as measured by thermocouples, and is called ΔT and given in degrees centigrade. We aimed at a ΔT value of 320°C for all the bursts. The actual values achieved were:

Shot No.	Sandia Burst No.	ΔT	Date	Time	δt
				h m	h m
1	489	317°C	5/14/71	1935	
2	490	296	5/15/71	0932	
3	491	317	"	1227	3 55
4	492	322	"	1452	2 25
5	493	321	"	1653	2 01
6	494	315	"	1852	1 59
7	499	313	5/17/71	1817	
8	500	321	"	2031	2 14
9	506	317	5/18/71	1834	
10	507	318	"	2034	2 00
11	514	313	5/19/71	1831	
12	515	319	"	2030	1 59

The last column, δt, gives the time in hours and minutes between bursts. A separate test box was made up for the 741 transfer function measurements, so that a Tektronix 575 curve tracer could be used just for the 9704 gate measurements. A Tektronix 7004 scope was used for the 741 transfer function pictures. Twelve scopes were used in the measurements. A scope was used to be sure only one trigger was delivered to all the pulse generators and scope triggers, since

occasionally the Sandia trigger circuit would create a double pulse. A typical timing sequence for the pulse reactor is shown below in Figure 85.

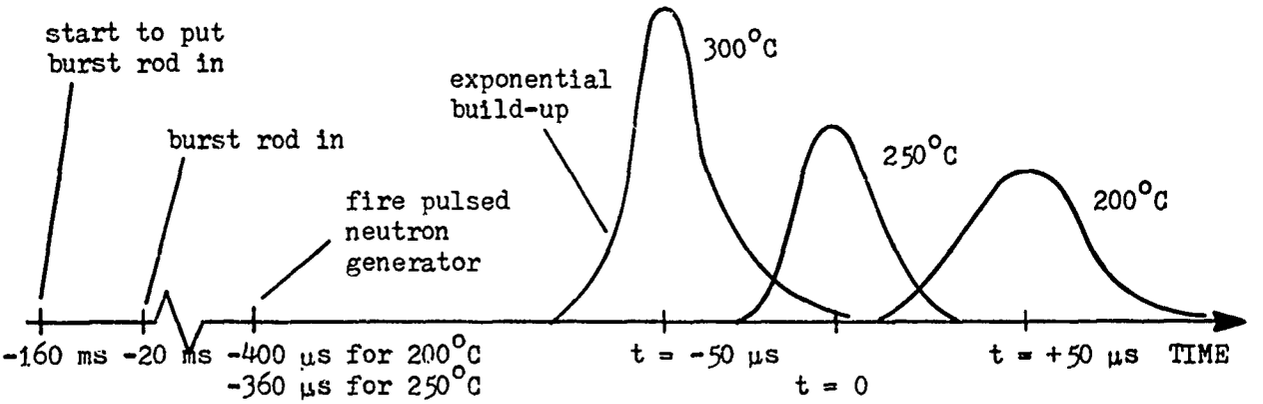
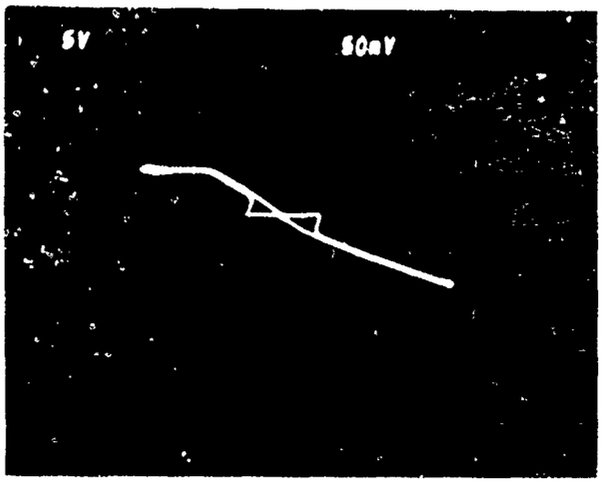


Figure 85. Pulse Reactor Timing Sequence

A type of radiation damage observed on the 741 op amps after neutron exposure at the closest position of the SPR is shown below in Figure 86. The input-output voltage transfer characteristic takes on a butterfly shape in the center. This is a permanent degradation of the device.

DATE 5|19|71 741-11

PHOTO
SCOPE 10
POST 12
____

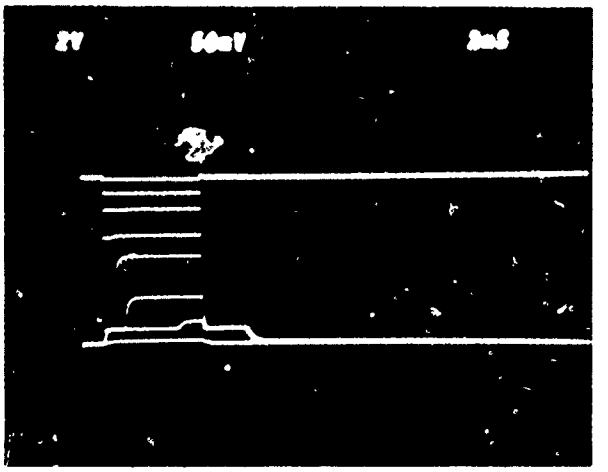


V1= e_o = 5V /DIV H= e_i = 50mV/DIV
V2= = /DIV Rf/Ri = 68K/1K P_{oo} = 1A

Figure 86. Effect of Neutron Radiation on 741 Op Amp Input-Output Characteristic

If this degradation is observed in a time domain oscilloscope waveform as shown in Figure 87, the output appears to take on a "top hat" which builds and grows on top a low level pulse. With increased input signal the top hat becomes larger and initiates earlier.

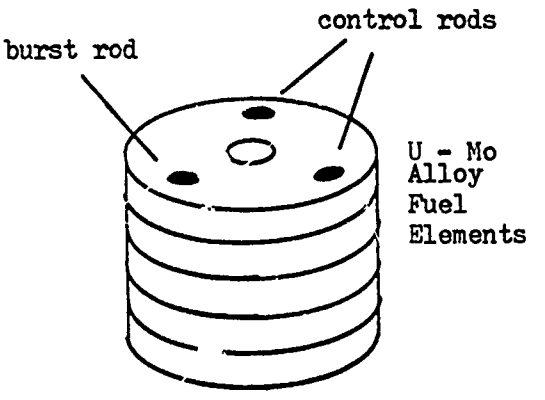
PHOTO
SCOPE 10
POST 12
#



V1= e_i = 50 mv/DIV H= t = 2 ms /DIV
V2= e_o = 2 v /DIV R_f/R_i = 68K/1K

Figure 87. Effect of Neutron Radiation on 741 Op Amp Pulse Response.

A sketch of the reactor core is shown below.



Schematic of Reactor Core

The Uranian-Molybdenum alloy fuel elements of the core expand 20 to 30 mil during burst, which is enough to stop the fission chain reaction process and terminate the pulse.